Designer/Researchers/ Company	M. del Campo, A. Fure, W. McGee, S. Manninger, A.Flexer Taubman College of Architecture and Urban Planning University of Michigan	Joris Laarman Lab	Mediated Matter, MIT Media Lab N. Oxman, J. Laucks, M. Kayser, E. Tsai, and M. Firstenberg	Hack and Lauer - For Garamazio Kohler Research	Joris Laarman	Stefanie Mueller, Sangha Im, Serafima Gurevich, Alexander Teibrich, Lisa Pfisterer, François Guimbretière, and Patrick Baudisch, UIST'14
Project Title	Automomous Tectonics	MX3D - Resin	Freeform 3D Printing: Towards a Sustainable Approach to Additive Manufacturing	Mesh Mould	MX3D - Metal Printer Dragon bench	WirePrint: Fast 3D Printed Previews
Date	2012	2012	2013	2012-2014	2014	2014
Material	n/a	Fast curing resin	High Density polyethylene(HDPE) (straight from pellet form)	ABS Plastic Filament	metals such as steel, stainless steel, aluminium, bronze or copper	PLA or ABS (ABS the preferred and used)
Extrusion Diameter	n/a	n/a (thicker - ~8mm)	Variable 10mm round extrusion - 8mm triangular extrusion (initial tests) After which interchangeable tips - 3mm extrusion nozzle for 3.5mm extrusion. Creation of unique profile like ribbon/flat (3mmx16mm) and hollow tube.	1.5mm + 2.5mm	n/a	0.7mm as ideal
Printer speed	n/a	n/a	n/a	n/a	n/a	Unspecified, but fast on extrusion and slows at peaks.
Size / Time Info	n/a	n/a	n/a	80 x 60 x 8 / 10 Hours (on small Ur5 Robot print)	n/a	17 x 17 x 24 cm
Temperature	n/a	n/a	130	n/a	n/a	ABS 230 - 250
Other Specified Info	note on scalability - understand the resulting model as a 1:1 model, which means that the process is per se the construction method.	n/a	Multi-strand nozzles designed to be longer and thinner for increased agility when printing more complex structures. Revised multi-strand tip utilizes 5 thicker diameter holes at the centre and along to outer perimeter, allowing for balance between quickly cooling strands for structural support and thicker slower cooling strands, which retain more heat to allow for better reconnection to existing cooled extrusions.	Volume Fraction 2.5%	We are developing printing strategies for different kinds of 3D-printable 'lines.' Vertical, horizontal and spiralling lines, for instance, require different settings, such as pulse time, pause-time, layer height or tool orientation.	8.5* faster than traditional printing on same printer. Unreachable areas noted and toolpath angle threshold due to print nozzle angle to avoid collisions with existing geometries.
CNC Device	KUKA KR125/2 Robot Arm	Robot arm	KUKA KR5 sixx R850 robotic arm	Small Ur5 Robot for smaller scale tests Larger scale Experiments on ABB Robotic arm mounted on mobile platform	Industrial Robot arm	Kossel mini 3D printer used but in theory any compatible FDM 3D Printer
Device axis	6 axis	6-Axis	6-Axis	6 -Axis	6-Axis	3
Extrusion device	Thermoplastic deposition system	n/a	Custom built extrusion tools.	Combination of custom machined parts and off the shelf 3D printer components.	Advanced welding machine	Kossel mini 3D printer extruder
Cooling devices	n/a	n/a (But video shows two blowers beside nozzle)	active air-cooling unit	Pressurised air directed at the extruder tip.	cooling pipes	Two air jets that are controlled by a solenoid valve to the print head
Specified Programmes	n/a	n/a	Rhino - modelling custom parts	n/a	n/a	Unspecified, but is it's own developed software; Wireprint.
Unique Printing Techniques	Computer/ algorithm driven with no finite form to be output. Less specific human input.	Only moving vertically/horizontally. No sharp bends or downward motions. Only showing small amount of curvature.	Spider informed multi-head extruder.	Variable structural mesh patterns - to vary locally and adapt accordingly to performance requirements	Instead of extrusion It is more welding based - not really continuous 'freeform' extrusion but built up spot welding, in a linear motion.	Only horizontal layering. Allowance for 'layerwise' detailing to be mixed with spaceframe structures, so both traditional layering and spaceframe layering can be sued in one print.
Freeform Technique	Loose banding type approach.	Linear curves growing vertically/horizontally.	Multi head extrusion freeform tests.	Banding - Parallel vertical zig-zag structures with connecting strand between	Small amounts of molten metal at a time, to print double curved lines in mid air.	Banding
Use of Pulling/ tension during cooling	None- Lets the material form naturally and respond to gravity	Not much as the line is built up slowly almost in layers - in which a small dollop of material is placed on to the previously extruded and cooled material, in saying which the print lines are dominantly vertical, relieving need for tension on downward motions which are most troublesome.	Fairly naturally freeformed and erratic - not much pulling / tension visible.	Stopping at apex' of triangles indicates it uses longer time staying in that position for cooling before changing direction.	Not much as the line is built up slowly almost in layers - in which a small dollop of material is placed on to the previously extruded and cooled material, in saying which the print lines are dominantly vertical, relieving need for tension on downward motions which are most troublesome.	Use of tension as upward motions is always vertical, stopped to cool, then angles are printed in downward motion when start and end point are specified.
Context	Research based autonomous structure experiments.	Experimental/ Research based	Architectural / Design based Research "Applications for this novel process are varied and range from product fabrication to furniture and architectural scale construction"	Robotically fabricated spatial meshes as reinforced concrete framework.	Experimental / Furniture	Fast preview for designers, to allow for iteration before final print. To make rapid prototyping made more rapid and lower fidelity.
Scale	Mid scale - experimental/protoarchitectural.	Small/mid scale Experimental/ product scale	Mid / large mid scale experiments but intended for large architectural scale application.	Mid / Large - proto-architectural / architectural	Mid/large Large bench	Small scale product (desktop printer scale)
Claims of differentiation	Autonomousness" - Autonomous robots are robots that can perform desired tasks in unstructured environments without continuous human guidance. here " Autonomous Tectonics begins to diverge is in the introduction of a feedback loop between resultant form and the subsequent steps of production. In a follow up step, the robot recognizes, via a camera as sensor, the most solid points of the model which allow for a solid continuation of the material deposition process"	"This method makes it possible to create 3D objects on any given working surface, independently of its inclination and smoothness, and without a need of additional support structures." Unique through use of resin.	"Novel design approach for 3D printing without additional auxiliary structures" Sustainable approach to additive manufacturing and digital fabrication at large, and point towards new possible directions in sustainable manufacturing.	Ability for exploitation of robot arms onsite dexterity. Alternative convention to conventional framework.	For the first time we can 3D print large-scale objects using high-quality, strong, self-supporting materials.	Not for final output or experimental intent, but for rapid prototyping and form previewing. Software focused output rather than outcome based. Can make almost any form printable.
Future directions/ later works / Other projects	Autonomous Tectonics II	This project is precursor to MX3D Metal Printing	Mainly silk / nature based design strategies moving away from the technicalities of freeform 3D printing to become more experimental/conceptually based. e.g.. Robotically Controlled Fibre-based Manufacturing as Case Study for Biomimetic Digital Fabrication (2013) Silk pavilion : A case study in fibre-based digital fabrication.(2014) As well as specifically mentioned future developments "future work may explore the further development of active heating and cooling at the tooltip, allowing for greater freedom of possible print geometries. Larger printed systems may be explored through leveraging the strand-like nature of larger printed 'cells' that utilize fibrous interfaces at their edges to assemble a larger fibrous aggregate system. "	Concepts for the development of faster multi nozzle print heads, inspired by inkjet printers are currently under development. They are currently working on a similar project that isn't extrusion based but develops fully automated bending and welding process for meshes fabricated in 3mm of steel wire - same context.	MX3D metal 3D printed Bridge in Amsterdam, installed across the Oudezijds Achterburgwal canal, 2016. Current project - the butterfly screen. Experimental sculptural screens. Working towards multi material gradient from bronze to steel. Arc Bicycle - Stainless steel printed frame. "The combination robot/welding machine is driven by different types of software that work together closely. This will eventually have to end up in a user-friendly interface that allows the user to print directly from CAD. "	"For future work, we plan to explore how fast 3D printing allows for novel types of interfaces that close the feedback loop between digital editing and physical fabrication. "
General Notes/overview	Contemporary approaches use the intelligence of emergent conditions or the possibility of responsiveness in a robotic setup (computer + robot) to create autonomous reactions in the system. Gravitates around the idea of harvesting those ideas to apply them within the architectural realm. Relies heavily on aspects of self-control and independent decision making processes, based on an intimate relationship between the perception of the machine (camera), the basic command of the algorithm (deposit, pull, connect) and the vertical motion induced to create a vertical figuration.. Following the first deposition process, which is defined by the designer, the autonomous behaviour of the algorithm commences its operations: the deposition head is equipped with a camera which serves as a scanner. The robot analyses the general condition of the first set of depositions selecting the points with the highest stability to continue the process.	3D printing like this is still unexplored territory and leads to a new form language that is not bound by additive layers. Ignorance of base structure and locality. Neutralisation of gravity during print process through material and innovative extrusion technology. Manufacturing structures of almost any size and shape. Research don in collab with IAAC	Focus on sustainable manufacturing and nature informed design processes through eliminating support material in using extrusion and material systems to cool material upon extrusion, using a KUKA robotic arm. Proof of concept and experiment based paper. Heavy focus on material systems in nature, reactions to various contextual factors and stimuli. Looking at specifically silkworks and spiders, and their variation in deposition, and natures optimisation of material usage. Initial small scale tests using ABS to test the concept of drawing a fluid plastic material through space. Testing of multistrand extrusion of HDPE in space.	Limited load capacity but greater onsite dexterity. Widens scope and possibilities of digitally controlled fabrication. Small dimension and low mass make them able to be applied directly to site, and equip with mobile platforms and sensors can respond and react to environments. Helps shift away from 'one size fits all' thinking and encourages variation and differentiation. "On-site dexterity" could inspire onsite creation of furniture directly into desired context (for larger scale furniture/installations?) Movement towards variation and differentiation relevant to customisable intentions.	Dragon is a sculptural and structural bench created by the MX3D metal printer. Ability to print in metals such as steel, stainless steel, aluminium, bronze or copper - without support structures. Developing 3D printable 'Lines'	Unique context focus. Making 3D printing as a rapid prototyping tool faster and more efficient in being such. Focus on the software it self and how this can be used by consumers. Use of strictly horizontal banding approach makes it more applicable to multiple forms.
Quotes	"In contrast to systems such as concrete casting, vacuum forming, or roto-molding, which utilize a formwork in order to give a system a specific shape, autonomous tectonics rely on a set of rules that trigger a behaviour in the robotic system in order to erect spatial figurations. In this respect the system is capable of creating emergent behaviours within a system of material aggregation." "It was the field of engineering that first utilized robots in the execution of building designs. This development was driven by very pragmatic reasons, rather than the explicit desire to innovate."	"Unlike 2D layers that are ignorant to the structure of the object, the 3D curves can follow exact stress lines of a custom shape." "Opportunity to create objects on any given surface, independent of its inclination and smoothness, and without need for additional support structures"	"In all of Nature's systems, the optimization of material usage and hence metabolic cost plays a necessary role. In tensile systems such as spider webs, there is little material waste as structural support is an integral part of the web design" "The multiple strands have the potential for multiple-strand bundling as a way of providing additional support (as the structure progresses in vertical space) and self alignment due to the forces of gravity. "	"Not defined and limited by its kinematics and offers an opportunity not only to customise parts but beyond that the entire fabrication process." "The unification of the two conventionally separate requirements of concrete – the reinforcement and the formwork – into one single robotic fabrication process, can produce an additive and waste-free, material-efficient and geometrically unconstrained method of fabricating complex non-standard concrete constructions."	"For the first time we can 3D print large-scale objects using high-quality, strong, self-supporting materials."	"Even though considered a rapid prototyping tool, 3D printing is so slow that a reasonably sized object requires printing overnight." "WirePrint can print these overhangs..(90deg) because the string of extruded material is put under tension until it is completely sturdy." "Our validation shows that in combination, these two approaches indeed lead to a substantial speed up of up to a factor of 10 and thus allow designers to iterate more often" "The main objective of the mechanical design behind Wire-Print is to maximize the stability of the produced objects while minimizing printing time."
Opportunities+ beneficial information- in Relationship to my Thesis	Letting the material and process inform direction. Embracing viscosity of material as well as designing it.	Interesting manifesto in stating that it allows the print to be ignorant to any surface. Use of unique material. Printing from vertical plane rather than just the ground is interesting and could have unique potential.	Use of different diameters of the strand in multistrands tests was clever to have some supportive faster drying elements and some slower- better bonding sections.	Discussion about onsite dexterity and differentiation from prefabrication is valuable. Movement towards variation and differentiation relevant to customisable intentions.	Interesting manifesto in stating that it allows the print to be ignorant to any surface. Use of unique material especially in the strength and longevity of metal.	Unapologetic use of freeform 3D printing - no claims that aren't fulfilled and transparent in settings and how it works. Pausing at peak while in tension. Integration of 'hybrid' layering systems to create variable fidelity sections.
Hindrances - That may inform my Thesis	Irregularity/ Spontaneousness of process less appropriate for end product production.	Mostly only going horizontally/ Vertically No downward or sharp turns mean that It could be a limited process.	Providing material connectivity to plastic parts previously cooled and hardened found difficult. It was also found upon attempting more complex path planning and part printing exercises that a longer extrusion tip length allowed for much greater flexibility in the manoeuvrability of the extruder while attached to the six axis robotic arm	Still heavily layer/banding based process. Later claimed (in mesh mould metal) to be weak "Digital Fabrication focuses on the translation of the structurally weak polymer-based extrusion process into a fully load-bearing construction system."	Almost still layering in a sense that it is not constant extrusion, but small dots of metal welded upon the next. Meaning still vertically/growing upward restricted creation.	Strictly banding based Little aesthetic considerations
Reference	Del Campo, Fure, McGee, Manninger, and Flexer, n.d.	Joris Laarman Lab, 2012	Oxman, Laucks, Kayser, Tsai, & Firstenberg, 2013	Hack & Lauer, 2014	Joris Laarman Lab, 2014	Mueller et al., 2014

Designer/Researchers/ Company	Branch Technology	Jiang et al. Bartlett School of Architecture	Hyunchel et al. Bartlett School of Architecture	Yuan, Meng, Lei & Zhang	Disney Studio x MDC
Project Title	Cellular Fabrication	Space wires - Filamentrics	Curvoxels - Spatial Curves	Robotic Multi-dimensional Printing Based on Structural Performance	Hybrid Phantasm
Date	Founded 2014	2014	2014-2015	2016 - Robotics conference	2015
Material	n/a	n/a	ABS Plastic filament (2.85mm)	ABS + PLA tested ABS Found to be superior for this context.	PLA/HDPE
Extrusion Diameter	Unknown - Thicker - star shaped extrusion profile	n/a	~4mm	n/a	n/a
Printer speed	n/a	n/a	3mm/s - 30mm/s Most prints around 17mm/s	n/a	n/a
Size / Time Info	7.5m x 17.5m x 3.8m Robot arm	n/a	n/a	n/a	n/a
Temperature	n/a	240deg		230 and above	n/a
Other Specified Info	Algorithm used to create both geometry and robotic motion to construct complex geometries in open space.	n/a	Increased print speed by creating steady temperature and high torque, Through 2 motors and 3 heaters	Explanatory diagram of custom mechanical systems	n/a
CNC Device	Large KUKA robotic arm Gantry	Small robot arm - Model n/a	Small robot arm - ABB IRB1200 + ABB IRB1200	KUKA Robot Arm	KUKA KR150 Robot Arm
Device axis	6-Axis	6-Axis	6-Axis	6-Axis	6-Axis
Extrusion device	n/a	n/a	Range of custom built printing heads 4 generations of models from 1 - 3 nozzles	Custom made - specifics fig9.	BAK Double ExOn8 Extruder
Cooling devices	n/a	n/a	Custom Air Compressor cooling system	4 custom cooling air tubes pointed at nozzle	
Specified Programmes	n/a	n/a	n/a	n/a	KUKA aprec, Grasshopper, Rhino.
Unique Printing Techniques	Star shaped extrusion profile allows for more surface area and thus faster cooling time and allows for larger diameter.	Moving towards less layered approach	Printing in Voxels rather than bands - desired form deconstructed into voxels and then each voxels freeform path calculated. Use of finite analysis to inform structure density.	Spider informed multi-head extruder.	Lets the material and prints fail and embraces these. Tectonically driven rather than structurally.
Freeform Technique	Banding	Banding - Space frame but more Three-dimensionally explorative	Freeform Voxels.	Multi head extrusion freeform tests.	Layered. I would call in between of traditional FDM and freeform printing.
Use of Pulling/ tension during cooling	Unsure - extrusion in star form relieves need for quick cooling during tension - but not talk of or shown explicitly. But seems to print faster on lines that are unsupported allowing for more cooling time and more tension between printer and point of security while cooling.	Unspecified and hard to tell.	Unspecified but seems like little - initially slow printing time means cooling takes place constantly meaning less tension needed and more curvilinear toolpaths can be achieved. But later on in research speed supposedly through improved technologies - creating steady temperature and high torque, Through 2 motors and 3 heaters	Little - multi extrusion beads are used to help define position of the line meaning less tension is needed.	None/little - Lets the material form naturally and respond to gravity - but printed sideways so most parts are printing horizontally and little vertical motion.
Context	Architectural Construction- "virtually unlimited design freedom using economical construction methods."	Research - Computational design methodologies for large-scale 3D printing	Varying contexts - Architectural research background Columns, Chairs and staircases exemplified Architectural structures proposed and rendered.	Architectural Research	Experimental (Architecture based)
Scale	Large Architectural	Mid/large Printed mid scale, and joined to become proto-architectural scale	Mid proto-architectural / Furniture	Mid / large mid scale experiments but intended for large architectural scale application.	Mid scale proto-architectural context
Claims of differentiation	Nature builds sustainably and efficiently. Material comes at a premium. Form is unlimited. Complexity is free. Its results are full of beauty and wonder. Branch Technology is changing the way that we build. We are asking the question, "what if you could build like nature?" "Democratising Design"	"Filamentrics intends to overcome the formal limitations of space frames, avoiding its homogeneity by introducing robotic plastic extrusion. Printed structures with a high degree of fine resolution and complex hierarchy can be achieved on a large scale within a relatively short period of time."	Voxel based	Structural optimization and ongoing technical analysis to adapt to different materials and design requirements. Spider silk informed multihead extrusion	Material and process driven system rather than form / construction based. "the designer does not create form, but the form created by the set of rules defined by the designer."
Future directions/ later works / Other projects	Building winner of their 'Home Design Challenge" To create world first freeform printed house in 2017	Unspecified.	Unspecified.	"Further research will be conducted in order to apply this structure performance-oriented multi-dimensional printing strategy to architectural fabrication. This will include further research of printing materials, respectively high strength and rapidly solidified materials that would expand the range and scale of design products." "diversified printing strategies will be developed with new combination of first and secondary structure."	Abstract further and push the process. Mentioned printing the same form in a standard layered printing process for comparison.
General Notes/overview	Inspiration from nature and building in an informed manner from it. Cellular fabrication is it's practical application - looking at minimal material solutions for wall assembly of organic forms - with precedents from nature they ask not how much can we print - but how little? Printed scaffolding intended to be filled with foam and concrete. "Freeform printing in open space is not constrained to the slow, layer-by-layer build process of traditional 3D printing." No support or highly controlled build environments. Cellular Fabrication allows virtually unlimited design freedom using economical construction materials. All construction projects - every home, every office - can enjoy cost effective design freedom - democratizing design freedom.	Using computational methods to create highly complex proto- architectural structures. "researches computational design methodologies for large-scale 3D printing with industrial robots, taking logistical, structural and material constraints as design opportunities to generate non-representational architectural spaces with extreme information density." Asked to situate their research in relation to fundamental structural paradigms and strategies such as space frames, lattices or vaults to then subsequently challenge the existing model	Voxel based process in which each voxel has a unique freeform printing path that is layered / build upon to create a three dimensional form. Application of different material characteristics created by varying extrusion diameter from a three headed extruder. Development of continuous curves in which each voxels path connects uninterrupted to the next creating a continuous toolpath. Development of different application ideas e.g.. staircase and chairs - as well as computational development of architectural structures.	seems to propose similar concepts of space frame banding approach like other projects - seems to only show physical experiments of Spider-informed multi extrusion research.Emphasis seems to be on technical and analytical approach of the project. Interface between layers of traditional printing methods mean material strength cannot be sufficiently exerted, and higher precision can improve this - but with this cost is very high.Benefits are height printing in space, and ability to integrate various performative optimizations within design and fabrication process. Flexible printing method and constant data feedback between design and fabrication platform improve structural rigidity. 3D technology far from meeting the requirements of building construction due to mass amount of material and structural considerations needed. Spider-web inspiration for developing a new printing profile by adding multiple wavy auxiliary curves to the main curve for greater structural performance and resisting bending force. ABS vs PLA analysis.	Looking at castles - asymmetry and proportions. Openings and arches - from which they tried to avoid creating a particularly designed object. Begun with topological optimisation and applying loads and support systems to tease it into a form/positions you potentially wouldn't draw. Synergies to the gothic came out of the process. Adding random increments into curves. Homogeneity, distinct separation of processes. trying to do something different from others. Finding synergies between their process and what was happening in gothic architecture. Not fully designing a thing before construction. Material driven rather than coming out with a specific thing. You can pull it to get varying consistencies and the reveal factor you can get with stacking. Iterative process looking at particularly interesting ideas and expanding on which. Not robust processes, don't need high degree of control but embracing those flaws/differences. Expressing character through materials and textures. e.g. evil.
Quotes	"We create the complexity of a cellular construct into which economical construction materials are applied to provide the function and strength of a wall assembly. Composite structures are created using the same methodology with which nature builds. Like bones in our body or trees in the forest, optimized geometries are made strong and functional by the material filling the matrix. The interior and exterior skins can then be finished in any fashion." "Branch is moving to a minimal material solution. Instead of asking, "how much can we 3D print?", we are asking, "how little?" "Branch Technology combines novel 3D printing technology, conventional construction materials, and large-scale robotics to build in a new way." "Our algorithm creates both the geometry and robotic motion to construct complex geometries in open space, without the use of support materials or highly controlled build environments. United with tried and true building materials and methods, this delivers a	"As architects, we can design for infinite resolution and density of information, controlling the deposition of millions of material particles. Yet there is a lack of design methodology to harness the full potential of computational power and computer-controlled fabrication. When compared to historic architecture, for example the Gothic, computational experimentation is still not able to successfully generate the same level of fine detail, hierarchy and information-density." "The use of custom design and fabrication algorithms makes it possible to amplify efficiency, where material capabilities such as porosity or connectivity are constantly linked to structural behaviour."	"This research, which has overcome the limitations that previous digital architecture had, or in other words having overcome the gap in design and fabrication methods, is determined to be able to create a new architectural aesthetic." "Through the proposal of new design methods, it is expected that there can be change and creation of various aesthetic values."	"The structural behaviour of the design is optimized through the consistent negotiation between material analysis and structural simulation in both virtual and physical environment, together with the implementation of sensor input and real-time feedback between construction tools and simulation interfaces. The printing tools are designed with additional extruders and nozzles of various dimensions to adapt to different materials and design requirements."on past AM techniques "The printing process is a simple formation process and excludes inherent structural logic of the product." "Although the current 3D printing technology is called three dimensional, it only refers to the three dimensional volume of end results." all p 92/93	"Viscosity to the material beyond what you can produce in the digital environment." "inscribing the unknown within the known" "Give a sense of the material that you can see rather than fixing a presubscribed form or structure onto a material process and try to replicate your digital form or environment."
Opportunities+ beneficial information- in Relationship to my Thesis	Star shaped profile a clever way to increase diameter for strength without hindering cooling time which is counteracted by the increased surface area. They seem to exemplify the most radical curves and sharp direction changes in prints.	More complex an varying approach to toolpath - rather than consistently spaced materials. Unique/abstract form approach.	More consideration to aesthetics. Product scale application. Variation of Extrusion bead diameter. Unique approach to freeform process.	Technical information like comparison of ABS to PLA. Bending and shearing experiments and print strand diversion from toolpath could be a good comparison to see how my test compare. Explanations of electronic control system may help inform if I come to customising large extruder.	Letting materials and failures be of value and embrace serendipity.
Hindrances - That may inform my Thesis	Scaffold structure is consistent and lacks options of variation.	Computational exemplars of ideals far exceed the complexity of the final prints/ outcomes.	Toolpath is somewhat unruly and could be considered more purposefully. Dense use of material. Still a ground - up approach.	ABS limited in strength in resisting bending and shearing forces.	Irregularity - potentially hinders for creating end product quality - but informative for iterative process.
Reference	Branch Technology, n.d.	Jiang, Wang, Ahmed, and Chen, 2014	Hyunchul, Amreen, and Xiaolin, 2014-2015	Yuan, Meng, Yu, & Zhang, 2016	Disney Design Studio, RMIT Architecture & Del Campo, 2015

Designer/Researchers/ Company	Garamazio Kohler Research	Kam-Ming Mark Tam, James R. Coleman, Nicholas W. Fine and Caitlin T. Mueller	AA School of Archtecture - Project Team: Shajay Bhooshan Studio: Marta Bermejo, Ruxandra Matei, Vladislav Bek-Bulatov, Li Chen	Festo's Bionic Learning Network	Ai Build
Project Title	Iridescence Print / Other projects in "extruded Structures" course by G K Research	Robotics-Enabled Stress Line Additive Manufacturing.	Growing Systems	3D Cocooner	3Dp Technology - Affordable Large Scale 3D printing. + Daedalus Pavilion
Date	2015	2016	2016	2016	2016
Material	ABS Plastic Filament- coloured in pellet form and extruded in 3mm bead	PLA Filament (1.75mm)	"A biodegradable material" Most likely PLA	2400tex glass fibre thread and coating of UV-curing resin. Glass-fibre roving with 2400 tex for producing glass-fibre rods with 2 mm diameter and 60% fibre–volume ratio. UV plastic: 1-Vinylhexahydro-2H-azepin-2-on, acrylate mixture	"Biodegradable filament by Formfutura" "A large variety of PLA and ABS materials can be used and mixed within one object
Extrusion Diameter	2mm (+/-0.5mm)	n/a	n/a	2mm	Variable options (visually thickish)
Printer speed	n/a	n/a	n/a	10 mm per second	n/a
Size / Time Info	Max volume of 1.5m x 1m x 3m	n/a	n/a	Construction space of 450 x 300 x 600 mm	3.2m x 2.4m x 2.8m max
Temperature	210 deg (+/-5)	n/a	n/a	n/a	n/a (guess PLA temps)
Other Specified Info	Freeform horizontal connections of up to 70 cm with 5mm deviation - decreased pp 119 of iridescence print article. Cell length sides varying between 5 - 10 cm	The KUKA's 24 V signal outputs were monitored by the on-board Arduino and were used to start and stop the stepper motor/extrusion. Control of the stepper motor was achieved with an EasyDriver board that uses an Allegro A3967 motor driver chip.	n/a	Printed material hardened with UV light as the structure is formed. Just like a caterpillar, it spins filigree figures and customized lightweight structures from a fiberglass thread "The three-dimensional shape model of the desired structure is developed in the software and turned into a physical form by the spinneret. With this process, the body is not built up by traditional 3D modelling, but generated instead according to parametric construction principles. For this purpose, a set of geometric rules is stored in a specially developed program, providing the basic shape of the structure and the design parameters.	Ai Build also made use of NVIDIA GPUs for running a combination of computer vision and deep learning algorithms to increase the speed and accuracy of large scale 3D prints. Adaptive Resolution - Different layer height and extrusion thickness options are available with their custom built extruders.
CNC Device	Small Ur5 Robot	KUKA KR6 R900 small robot	Robotic Arm (Details unknown)	Festo Tripod EXPT-45	KUKA Industrial Robot
Device axis	6 -Axis	6-Axis	6	n/a	6
Extrusion device	Custom Built printing head	Custom extrusion module	n/a	Precision spinneret	Custom Build Extruders
Cooling devices	Compressed air system at room temperature	n/a	n/a	UV light: fibre-coupled LED; 365 nm; 9.3 mW	Unknown, looks like attached fan
Specified Programmes	n/a	Rhinoceros + Grasshopper Structural analysis through Karamba Surface design form-found using Kangaroo Physics. Robot instructions generated in RobotMaster, a plugin to MasterCAM.	n/a	Cinema 4D	NVIDIA GPUs
Unique Printing Techniques	Rotation at triangle Apex to assist sharp direction change. Pause at bonding points. Separate fabrication logic (speed, extrusion rate etc. relationship) developed for every fabrication method.	Printed on supporting surface milled from laminated MDF block. Thus not entirely 'freeform'.	Variable material deposition Feedback loops through scanning device and generative algorithm the adjusts the design in real time. (does not seem proven only suggested for future)	Only printing in linear extrusions - printing directly upward and then placing into position after curing. Additional cutter to create flat ends after vertical extrusion.	Mainly linear movements to create curvilinear forms.
Freeform Technique	Banding -	Simultaneous layering on supporting surface.	Variable, combination of human input, material freedom, and robotic extrusion.	Banding in only straight lines.	Banding, fairly consistent layering dimensions
Use of Pulling/ tension during cooling	Stopping at apex' of triangles indicates it uses longer time staying in that position for cooling before changing direction.	None - due to use of mould not freeformed unsupported structured require tension/ cooling time whilst extruding from printer.	Little, is manipulated a bit through human input and interaction, but proposal suggests use of multiple robotic arms, and feedback loops.	Extrudes and cures while vertical and under tension, then places in position.	Straight toolpaths suggest use of tension. Upward motions are often vertical, and angles are made down as there is then a set start(top of upward line) and end point to secure to (existing printed portions)
Context	*Research - Mid ground between architectural performance and still having freedom of research for novelty and visionary results. *Exhibition space.	Research - Technical based for 2.5D Surfaces.	Experimental proto architecture with intention of architectural	Experimental leading to product production.	Large scale 3D printing for anyone interested in using 3Dp
Scale	large Architectural	Small Small test scale with intentions of larger scale application.	Mid - Large scale - protoarchitectural	Small/ Mid Product scale intentions but currently smallish printing size limits	Mid-Large scale - Architectural, Proto-architectural, and when in collab with Zaha Hadid Design, furniture.
Claims of differentiation	"Iridescence Print is the first large-scale architectural installation to be automatically printed by robotic machines." Colour to exemplified continuous toolpath.	Tool path focus on structural efficiency using simultaneous xyz movements.	Use of multiple robots Suggested ability of adaptability over time, to remove and reprint using the same material. Allowance for the natural behaviour of the material.	End product production.	Large scale building solution for collaboration / use by anyone interested. Multi material printing of PLA and ABS. Adaptive resolution of layer height and extrusion thicknesses. Integration of computer vision and deep learning algorithms, and artificial intelligence.
Future directions/ later works / Other projects	Other experimental concepts of freeform extrusion process coming of what seems to be a course called 'extruded structures by Garamazio and kohler research.	Continue to investigate the material and strength behaviour of artefacts printed using the SLAM method Standardize and improve the SLAM procedures to achieve better precision Develop a computational framework to automate the generating stress-line-based structures and robot paths. Continue to explore and expand the design applications of SLAM.	n/a But guessed further proof of concept and development.	Proposed design of 'chair'	Unspecified
General Notes/overview	Iridescence Print is the first large-scale architectural installation to be automatically printed by robotic machines. Conceived as a spatially complex lightweight structure, the installation synthesizes a rigorous exploration of the architectural potentials of robotic extrusion of spatial meshes at full architectural scale. The multi-coloured installation was developed during the elective thesis "Extruded Structures" Custom coloured filament reels extruded to create tonally varying material. Exhibiting artist tools within the structure for exhibition context. - design adapts around these tools.	AM Framework for fabrication of '2.5D' surface designs. For materiality explicitly along principal stress trajectories. Non- defaulted filament orientation that stops resulting in variable stress behaviour and instead defines and follows optimal paths of material continuity for a given design boundary. Seeks to facilitate flexible design-space exploration and fabrication standardization. Filament orientation inherently link with strength due to weak fusion between horizontal layers. Limits durability and end-use application of AM. Motivated by the recognition of anisotropy in artefacts printed using conventional FDM methods.	The suggested context and claims of adaptably and functionality is quite far behind the physical printed pieces. Focus on the adaptability of the material and the ability to reprint. In between of experimental and output focused works. Variable material deposition, not restricted to layer or dispersion based systems.	Nature inspired 'cocoon' spinning. Delicate shapes and creates custom-made lightweight structures out of glass-fibre thread. Parametrically defined output creation.	Very dynamic use of form but simple use of structure. Good print quality due to consistent structure. Solid research into generating the process to be ready for use by anyone interested, computational and deep learning algorithms to help increase speed and accuracy, creating this high quality print. Selling as inexpensive solution.
Quotes	"Little amount of material is spatialised in a kind of open framework with different iridescent colours." "fluid design which is completely programmes to accommodate multiple functions"	Called "stress line additive manufacturing" (SLAM). "The proposed method achieves an integrated workflow that synthesizes parametric design, structural optimization, robotic computation, and fabrication. "Current 3D printing platforms conform to a traditional CNC-based paradigm (Schwartz 2013) in which machine operation operation is isolated from design." p.367/368 "Recognizing the directionally dependent performance characteristics of FDM processes, filaments are aligned to major axial networks of curvatures called principal stress lines." p. 368 "Layer-based conventions reduce aesthetic quality, material efficiency, and geometrical accuracy."-p.368	"The system can also negotiate at a larger scale maintaining its entropy – When two houses starting from different initial conditions change over time, one needing to grow while the other shrinks – an exchange of material can occur, balancing the system." "In the construction process, a robotic arm is utilized on-site, so as to quickly build with minimal disruption, including an elimination of the need for scaffolding, as well as an elimination of waste." "The robotic arm will be embedded with intelligence, being able to scan the environment and the printed geometry and provide feedback. It will also be equipped with a generative algorithm that will adjust the design real-time fully erasing the line between design and fabrication."	"From the virtual model to the finished product On a system like the 3D Cocooner, the virtual design program supplies the assembly instructions directly at tool level. This makes it possible to go digitally from the design to the finished product without detours via the otherwise usual sales, reduction and logistics channels. The declared objective – being able to supply batch size 1 at reason able costs using automated large-scale facilities in industry – comes one step closer with such solutions. " "The tripod receives the necessary positional data and control signals directly from an animation software program that is normally used to create virtual 3D models, computer graphics and simulations."	"3D Printing out of the box" "Printing is a fascinating technology that makes it possible to manufacture incredibly complex forms which would not have been possible with other methods such as moulding or milling. However, it is very expensive or nearly impossible to 3D Print large structures with today's technology due to the small size and slow speed of 3D Printers that are available on the market. Ai Build is developing 3Dp technology for 3D Printing large scale objects cost efficiently at a very high speed."
Opportunities+ beneficial information- in Relationship to my Thesis	Use of colour to highlight toolpath is appealing. Stating that you can take the space from down - grind it up and re-extrude and create a new form is interesting.	Technical information on stress lines placement for structurally efficient forms. Concept and explanations conform to my technical ideals and are well expressed. Exemplar of ideals of using toolpath fully simultaneously - but just on a support surface.	Suggestion of onsite-printing Variable material qualities	Precise an invariable process so potentially more reliable in quality. Exploration of new materials and their opportunities - not blowing needed. Printing vertically as an embraced technique	Use of the process for custom or bespoke large scale printing option.
Hindrances - That may inform my Thesis	Having to print in sections. Still heavily layer based/ banding method. Print quality possibly slightly lower than other projects.	Have to create mould first. Still a form of layering - although 3 dimensionally layering. Creation of 3d surfaces rather than 3D objects - hence defining process as '2.5D'	Irregularity/ Spontaneity of process less appropriate for end product production.	Fairly slow Sill banding Limited to straight print lines	Still a very consistent algorithm based material dispersion system, little response to form apart from frame morph
Reference	Gramazio Kohler Research, 2015	Tam, Coleman, Fine, & Mueller, 2016	Bermejo, Matei, Bek-Bulatov & Chen, 2016	Festo, 2016	Ai Build, 2016