Design of cellular structures for robotic assembly

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Faculty	Aerospace Engineering
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Faculty	Mechanical, Maritime and Materials Engineering

Appendices

DESIGN FOR our future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: Biront 5502
initials: A given name: Andreas
student number: 4580302
street & no.:
zipcode & city:
country:
phone:
email:

Your master programme (only select the options that apply to you):
IDE master(s): [x] IPD [ ] DfI [ ] SPD
2nd non-IDE master:
individual programme: - - (give date of approval)
honours programme: [ ] Honours Programme Master
specialisation / annotation: [ ] Medisign [ ] Tech. in Sustainable Design [ ] Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Dr. ir. J. Wu dept. / section: SDE/MF
** mentor: Dr. K. Masania dept. / section: AE
2nd mentor: Ir. E. Garner
organisation: 3mE
city: country:

comments (optional): Ir. E. Garner is a PhD student who is registered at 3mE and supervised by Dr. ir. J. Wu, from IDE.

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

TU Delft

Procedural Checks - IDE Master Graduation

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair: Dr. ir. J. Wu date: 16 - 02 - 2022 signature: Jun Wu Digitally signed by Jun Wu Date: 2022.02.16 09:03:32 +01'00'

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair. The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 24 EC
Of which, taking the conditional requirements into account, can be part of the exam programme: 24 EC
List of electives obtained before the third semester without approval of the BoE:

[x] YES all 1st year master courses passed
[ ] NO missing 1st year master courses are:

name: K. Veldman date: 18 - 02 - 2022 signature: Kristin Veldman Digitally signed by Kristin Veldman Date: 2022.02.18 11:21:33 +01'00'

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **. Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: [x] APPROVED [ ] NOT APPROVED
Procedure: [x] APPROVED [ ] NOT APPROVED

comments: But the human aspect is missing in the project, so it is on the edge of IPD, Mr. Jansen will discuss this with the chair.

name: Monique von Morgen date: 01 - 03 - 2022 signature:

Initials & Name: A Biront 5502 Student number: 4580302

Title of Project: The design of an assembly robot for advanced lattice structures

The design of an assembly robot for advanced lattice structures

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 14 - 02 - 2022 08 - 08 - 2022 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The field of design engineering has had a focus on lattice structures for a long time due to all its benefits. The main reason is its ability to construct different structures with same identical building blocks (voxels). Here we speak of Lattice structures as objects that are periodic in nature, continuously repeating unit cells that interconnect in three dimensions. These structures are an emerging solution to weight, energy and advanced manufacturing time reduction [1].

Lightweight structures are a critical part of modern engineering solutions. Lowering structural mass while increasing the system's performance leads to higher efficiency over all. Operating costs can be reduced and resources preserved. Lighter structures lead to lower fuel usage in transportation and thus support the fight against climate change. [2] Only solution for assembling now is manual assembly, which is labor intensive. This can be resolved by making use of the repeating unit cells. It results in a structure that is easily navigable by relatively small, mobile robots. The geometry of the cell can allow for high packing efficiency to minimize wasted payload volume while maximizing structural performance and constructibility. [3]

The idea for making assembler robots came from NASA who investigated in the cellular structures for reconfigurable space structures. This system would mainly be used for high-performance structures in harsh environments. The idea is to send an army of little robots together with a batch of building blocks to space. These armies will build structures on space stations or celestial bodies and maintain them.

These structures will only be suitable for use if the production and assembly can be automated. It is obviously hard to assemble such structures only using the traditional way by hand. Therefore a material-robot system has to be designed, where the robot and material work together to create a system that will reduce cost and time. However, the difficulties are in the robots moving along the lattice structures and connecting them together.

There have been recent studies to develop the most suitable building blocks and small robots that can locomote on and transport such voxels. Still, an integration of both voxels and robot in one system has to be developed to use this system for the assembly of large structures. As an extension on the thesis of Pranav Gawde [4], who developed the best suitable voxel, the research of Alex luijten (co-supervised by Dr. K. Masania from AE), who designed a robot that can assemble lattice structures [2], and the report of the Advanced Prototyping Minor: bridge and laser cut cells, where they redesigned the voxels for easier manufactering and looked into what use lattice structures could have for humans [5]. My study will be about how to reconfigure the assembly robot and the voxel to design an integrated robot-material system. So, that the robot can easily assemble, dis-assemble and repair lattice structures without compromising the benefits of these structures. This graduation project is part of Dr. J. Wu's ERC proposal "Space-time optimization for additive manufactering".

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[1]Mark Helou & Sami Kara (2018) Design, analysis and manufacturing of lattice structures: an overview, International Journal of Computer Integrated Manufacturing, 31:3, 243-261, DOI: 10.1080/0951192X.2017.1407456
[2]Luijten, A., Masania, K., Eichenhofer, M., & Studart, A. (2020, February). Self-assembling ultra-lightweight lattice structures. ETH Zurich. https://surfdrive.surf.nl/files/index.php/s/KHurGBdR3nNqCNq
[3]Ochalek, M., Jenett, B., Formoso, O., Gregg, C., Trinh, G., & Cheung, K. (2019, June). Geometry Systems for Lattice-Based Reconfigurable Space Structures. IEEE. https://doi.org/10.1109/AERO.2019.8742178
[4]Ravindra Gawde, P., Wu, J., & Balkenende, A. R. (2021, juli). Modularity in Lattice structures for Circular Product Design. TU Delft. https://repository.tudelft.nl/islandora/object/uuid%3Ab0fc5f9a-b4e1-455a-8bef-1c9a48054d87?collection=education
[5]Ornstein, O., Avontuur, F., Van Leeuwen, T., & Oschatz, Q.(2022, januari). Lattic: Advanced Prototyping Project 2022

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introduction (continued): space for images

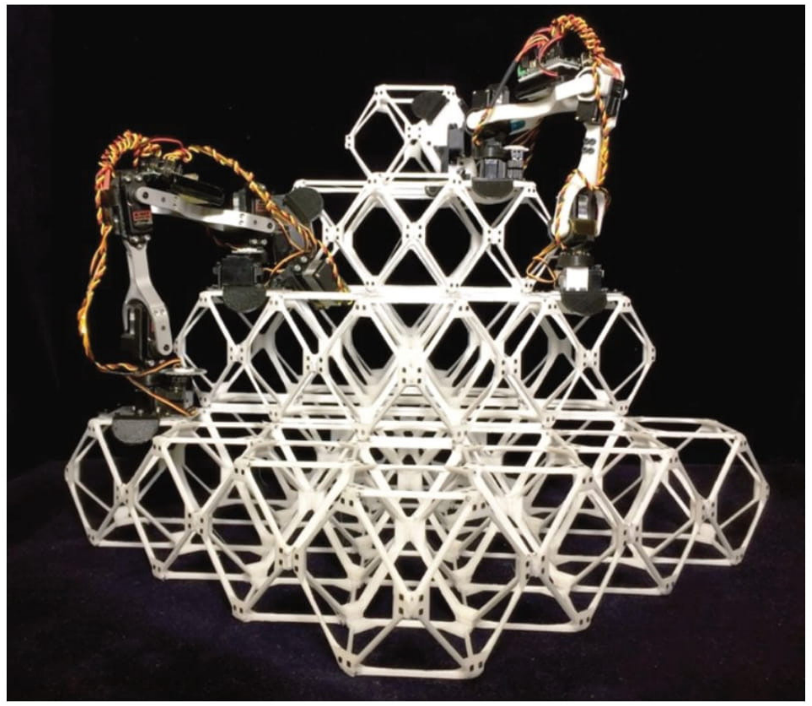

image / figure 1: Two prototype assembler robots at work putting together a series of small units

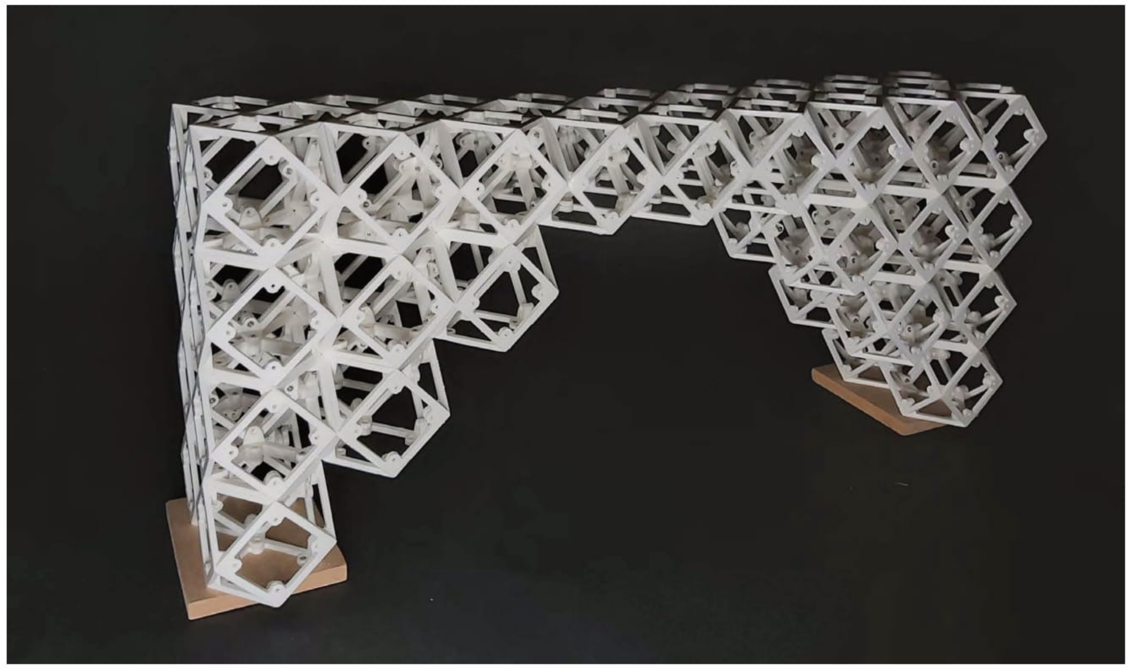

image / figure 2: Voxels fomed into a bridge by Pranav.

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Currently, there are sufficient studies about lattice structures, but only a few about robot assemblers and the integration of the assembly robot with lattice structures. In the studies about the integration most voxels shapes are different from Pranav's design and if they look similar there are still some problems to be solved.
Most of the limitations are found in the current technology used. The structural connection needs a redesign because using bolts and nuts causes difficulties in dis-assembly and repairs. As well as some designs currently only use magnets for alignment but can not be used as structural connections[1]. The robot itself has difficulties climbing vertically due to gravity but this would only be applicable in places with gravity. To move around the robot makes use of stepper motors where the limitation is the torque. Therefore, on board sensors would be useful to measure the torque and integrate new motors or redesign the system for the given motors. [2] Another constraint is that the robot only works in a controlled environment, and not yet in a dynamic environment. The ability to adapt to changing conditions is of outer importance. [1]
These limitations show us that there is still no success in the developing of a material-robot system consisting of mobile robots which can assemble, the previously designed voxels by Pranav. The assembly robot should be able to locomote on, transport, place and connect voxels. The system should be designed in such a way that the robots use the regularity of the structure to simplify the path planning, align with minimal user intervention, and reduce the number of degrees of freedom (DOF) required to locomote [2].

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[1]Jenett, B., Abdel-Rahman, A., Cheung, K., & Gershenfeld, N. (2019, July). Material-Robot System for Assembly of Discrete Cellular Structures. IEEE. https://doi.org/10.1109/LRA.2019.2930486
[2]Jenett, B., Cellucci, D., & Cheung, K. (2017, July). A Mobile Robot for Locomotion through a 3D Periodic Lattice Environment. IEEE. https://doi.org/10.1109/ICRA.2017.7989644

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

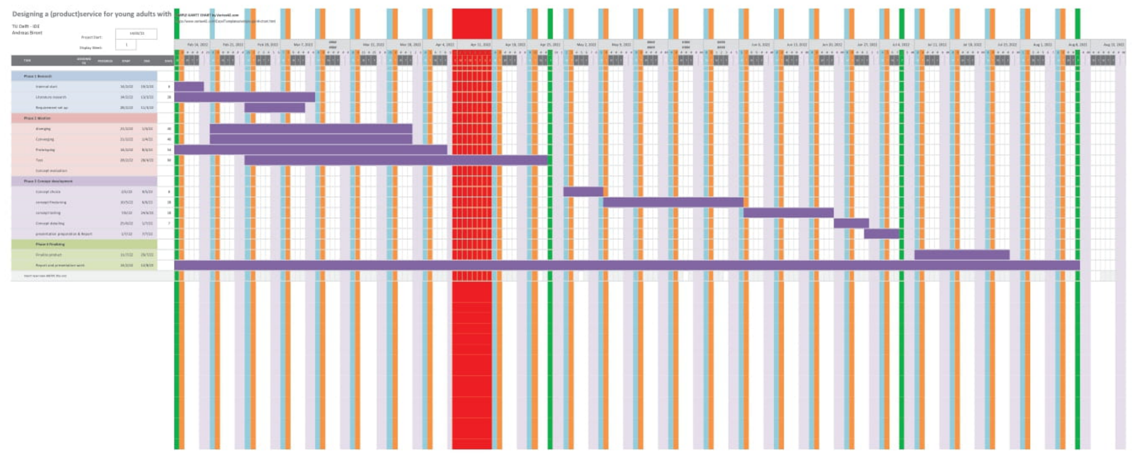
I will design and create an assembly robot based on its corresponding building blocks to efficiently build cellular structures in a controlled environment.

The aim of this project is to study and conclude the best configuration of material-robot system for assembling lattice structures. Prototyping and testing ideas and concepts will support the provided results and shows what configuration I ended up with. At the end of my graduation, I expect to deliver a fully working assembly robot that will be able to locomote on, transport, place and connect voxels. All aimed to build or deconstruct lattice structures. Next to this, we want to finalize this project by publishing this research as a scientific paper.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 14 - 2 - 2022 | 8 - 8 - 2022 end date



Within the Gantt chart the orange colored days are the days that I will be working on my student job. The red block is my one week vacation to visit my sister in Finland and the light gray colored days are weekends. Every Monday I am planning a meeting with the supervisors (light blue) and the green colored days are the 40, 80 and 100 day marks.

Plan for this project is to start a literature study parallel with analyzing, iterating and prototyping on the previously designed concepts of the voxels and robot. The literature study will consist of studying the automated assembly of lattice structures. This will include the how the robot locomotes on, transports, places and connects voxels. As well as what forces such structure should withheld when it is being manufactured by an army of small robots.

Getting hands-on as soon as possible is the best way of becoming familiar with the system. This will help me ideate on the most suitable configuration of material-robot system and reiterate. Prototyping and testing will help me compare the results of different sub ideas of placing and connecting voxels for example, so that I can integrate in one working system. The tests could include the efficiency of the system, How the robot locomotes on the structure and transports the voxels, etc. It might also include the durability of the system if robots would live on such structure, what other application this system can be used for, etc.

Finally, I will be concluding what kind of material-system is best for assembling lattice structures. If this system is more sustainable for future use and what it impact has on assembly, dis-assembly and repair of lattice structures.

Personal Project Brief - IDE Master Graduation

TU Delft

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

Combining my Aerospace engineering and design skills:

In this project I would love to combine my aerospace bachelor and my IPD master skills and knowledge that I gathered in the last couple of years. This period is also the last time I will be able to work on a project that lies out of my comfort zone, which provides the opportunity to learn more skills. I can finally reuse my prior knowledge about programming in Python and C++. As well that this project give me the chance of working on robotics and path planning where my engineering skills will help me out.

For the master IPD, I will be using my design thinking and skills to iterate, design and develop concepts that can be weighted to one and another. I think that the design masters will help me to explore more ideas and take steps back where needed to fully understand what I am doing. Looking at my skills, I started learning 3D modeling in rhino and grasshopper in the computational design elective. I am going to further develop these skills to efficiently redesign the existing robot and create customized components. During ADE I came into contact with basic electronics, where I learned more about hardware and how to assemble these parts.

Designing for the future:

I was always fascinated by space and what the future will look like. That is why I am happy that I can combine both studies I have done. I like to design for scenarios that we can not predict, this makes me curious on how things will look like and creates an open space to start generating ideas. I hope for a future that is sustainable for mankind where we can keep on living on earth but get the possibilities through design to go beyond the stars.

Personal learning goals:

I want to get a more in-depth knowledge about robotics and path planning algorithms. This will help me in my ambitions to be able to extend my hardware and software knowledge. I would also like to extend my skills as a designer, mainly in prototyping and iterative design. Designing, creating and testing will make me more comfortable with the hardware and software and create a fast pace to get good results. Eventually I want to learn the benefits of automation for people and be able to prove, with this project, that we can live with robots and that they will make our future easier.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Initials & Name A Biront 5502 Student number 4580302

Title of Project The design of an assembly robot for advanced lattice structures

Independant Properties

Number of attachments per voxel — **The number of attachments per voxel is considered as a measure of the complexity of the unit cell.**

Number of attachments per adjacency — **The number of attachments per adjacency is also considered as a measure of cell complexity, and is a function of adjacency and attachment types.**

Coefficient of Volume — **Coefficient of Volume is defined as the ratio of the volume contained within the convex hull of the voxel geometry to the space filling repeating volume that defines its assembly to the intended lattice geometry. For example, for a cuboct lattice, this can be either the volume of an octahedron to the volume of the cube enclosing that octahedron per simple cubic packing, or the volume of a cuboctahedron to the same.**

Average number of attachments per coefficient of volume — **The average number of attachments per coefficient of volume as defined above.**

Dependant Properties

Stiffness and Strength Scaling — **It is shown in the literature that stiffness and strength scaling are governed by the cell wall bending and can be determined using beam theory and dimensional analysis**

A few geometries are particularly well studied in the field of cellular solid materials. Where possible, empirical values for the stiffness and strength scaling were identified and cited herein. If experimental results were not available, computational estimations for the scaling laws were determined using the connectivity of the unit cell. This provided a coarse estimation of the behavior of the lattice depending on whether the structure is transverse bend or axial stretch dominated, in terms of microstructural behavior under load.

Tiling — **The tiling of the unit cell referred to the packing type of the unit cells once they were fastened to each other. Simple cubic packing (SC) occurred when consecutive layers of unit cells lay directly on top of the cells below them, i.e. simple cubic packing. Body centered cubic (BCC) tiling was defined as alternating layers of cells sitting offset to one another. Tiling and the spatial relationship of unit cells became important when characterizing the complexity of locomotion needed by the robot to move across the structure.**

Packing efficiency — The packing efficiency relates the deployed volume (the volume of a completed lattice) to the payload volume of unassembled voxels.

Volume allowance for robotic end-effector — The robotic endeffector must be able to access all attachment points in order to join unit cells to each other. It is presumed that a larger volume allowance offers more range of motion to maneuver to each attachment. This was calculated by determining the volume ratio of the largest clearance volume for the endeffector to enter and exit the unit cell to the total volume of the cell.

Strut Clearance Angle — The strut clearance angle, , was another metric related to end-effector clearance. It was defined as the angle between the vector orthogonal to the node and the adjacent strut. A larger angle provided more clearance for the end-effector to operate near the node.

List of requirements	Type	Specification	Validation
Voxel inter connection system			
Connection	Demand	The connection system should be integrated in the voxel	Prototype voxel
	Demand	The pin should be connected with only one movement	Connection system
	Demand	The connection system should make the overall system less complicated	Compare movements by the robot conducted
	Demand	The connection system should restrict sideways motion between two voxels	Test connection
	Demand	The connection system should restrict vertical motion between two voxels	Test connection
	Wish	The connection should should lock linear motion between two voxels	Test connection
	Demand	The male pin holders should not interfere with the strut clearance of the voxel	Test strut clearance
	Demand	The connection should restrict bending movement	Test connection
Lattice structure			
Assembly	Wish	A voxel should be able to be removed without removing surrounding voxels	Test connection system
	Demand	A voxel should be able to be placed without interfering with surrounding voxels	Test connection system
	Demand	The structure should be assembled autonomously	Test robot/manipulator
	Demand	The structure should be disassembled autonomously	Test robot/manipulator
Repair	Demand	Structure as a whole should be self supporting throughout the life and during assembly/disassembly/ repair/replacement process	Prototype structure
	Demand	A failure of one voxel should not affect the performance of adjacent voxels	Prototype structure
	Demand	It should be feasible to change one or a few voxels without affecting the integrity of the whole structure	Prototype structure
General	Demand	The lattice structure should be reconfigurable	Test connection system
	Demand	The lattice structure should have societal relevance	Interview people
	Demand	The lattice structure should be a potential improvement of the conventional solution	Interview people
	Demand	The lattice structure should have (dis)assembly on location	Test manipulator

Voxel			
Male	Demand	The voxel should have a weight of 420 grams	Weigh
	Demand	The voxel should be 200x200x200mm	Measure
	Demand	The voxel should include 5 pin bridges	Check submodule
Female	Demand	The voxel should have a weight of 326 grams	Weigh
	Demand	The voxel should be 200x200x200mm	Measure
General	Demand	The voxel should have two connection points on each side	Check submodule
	Demand	The voxel should be modular	Check submodule
	Demand	The voxel shape should make path planning more simple	Verify robot's path planning
	Demand	The voxel size should be able to change depending on the application	Check submodule
Robot			
Voxel placement	Demand	The robot should be able to place the voxel from each direction	Verify robot's path planning
	Demand	The robot should be able to place a voxel while standing horizontally	Verify robot's path planning
	Demand	The robot should be able to place a voxel while standing vertically	Verify robot's path planning
	Demand	The robot should be able to place a voxel that will be surrounded by 4 other voxels	Verify robot's path planning
Movements	Demand	The robot should be able to move horizontally	Test robot movements
	Demand	The robot should be able to move vertically	Test robot movements
	Demand	The robot should be able to move in one straight line without interfering with surrounding voxels	Test robot movements
	Demand	The robot should be able to move on structure while holding a voxel	Test robot movements
	Demand	The robot should be able to rotate to change direction	Test robot movements
features	Demand	The robot should be able to walk around with a voxel with a weight of 420 grams	Test manipulator
Feedback system	Demand	The robot should be able to know when to adjust its feet	Tactile sensors
	Demand	The robot should be able to know when a voxel is (dis)connected	Magnetic sensors
	Demand	The robot should be able to know its place on the structure with reference to the launch pad	Feedback testing
	Demand	The robot should be able to know when a voxel is placed	Torque sensors

End-effector			
Accesibility	Demand	The manipulator should be able to acces the inside of the voxel	Test end-effector
	Demand	The manipulator should be able to acces the connection system	Test end-effector
Connection	Demand	The manipulator should be able to connect a voxel with only 10 movements	Test end-effector
	Demand	The manipulator should be able to align two neighbouring voxels	Test end-effector
Movement	Demand	The manipulator should be able to hold the voxel while the robot moves	Test end-effector
	Demand	The manipulator should be able to rotate the voxel	Test end-effector
	Demand	The manipulator should be able to remove the voxel horizontally	Test end-effector
	Demand	The manipulator should be able to place the voxel horizontally	Test end-effector
Electromagnet holder	Demand	The holder should be able to rotate 90 degree	Test end-effector
	Demand	The electromagnets should be able to be activated seperately	Test end-effector
	Demand	The electromagnets should have an attracting and repelling stand	Test end-effector
	Demand	The electromagnets should repel to connect the voxel	Test end-effector
	Demand	The electromagnets should atrract to disconnect the voxel	Test end-effector
Environment			
Production	Demand	The structure should reduce production waste	Reusable
	Demand	The structure should reduce the waste stream	Reusable
	Demand	The structure should reduce disposal costs	Reusable
Use case	Demand	The structure should be able to work as a shelter	Test structural integrity

Robot End Effector								
BOM level	**Description**				**Qty**	**Units**	**Unit Cost**	**Cost (Euro)**
1	Hand palm				1	1		0
1	Arduino cables				10	10	0,09	0,9
1	Tactile sensors				2	2	25,6	51,2
1	Grippers				4	4		0
1	Servo gripper				2	2	4,2	8,4
1	Arduino				1	1	24,6	24,6
1	Translating mechanism				1	1		0
2		Servo			1	1	18,5	18,5
2		Linear gear			1	1		0
2		Circular gear			1	1		0
2		Servo holder			1	1		0
2		Rotation mechanism			1	1		0
3			Servo		1	1	18,5	18,5
3			Circular gear		1	1		0
3			bolt		1	8	0,4	3,2
3			Connection mechanism		1	1		0
4				Electromagnet holder	1	1		0
4				Electromagnets	2	3	4	12
4				H-bridge	2	2	4	8
				Total number parts	**35**		**Total cost**	**145,3**

The parts with zero euro indicate that these parts are 3D printed. Since these parts would be made out of other materials these prices are not yet known.

Appendix [E] Voxel Size Depending Factors

Mechanical strength

The scaling up of the concept for large-scale applications needs the modules to be strong enough to withstand the expected load based on the application. Based on these requirements, the sub-module strut diameter should be initially determined. And once that is decided, the voxel size can be determined based on the level of complexity the assembly for the application can handle. As seen in section 5.4, the smaller the module size, the larger the assembly components.

Weight requirements

Also in applications where the weight of the structure matters, it should be considered that smaller modules but large in quantity will have more fasteners involved that will increase the weight of the overall structure.

Manufacturing limitations

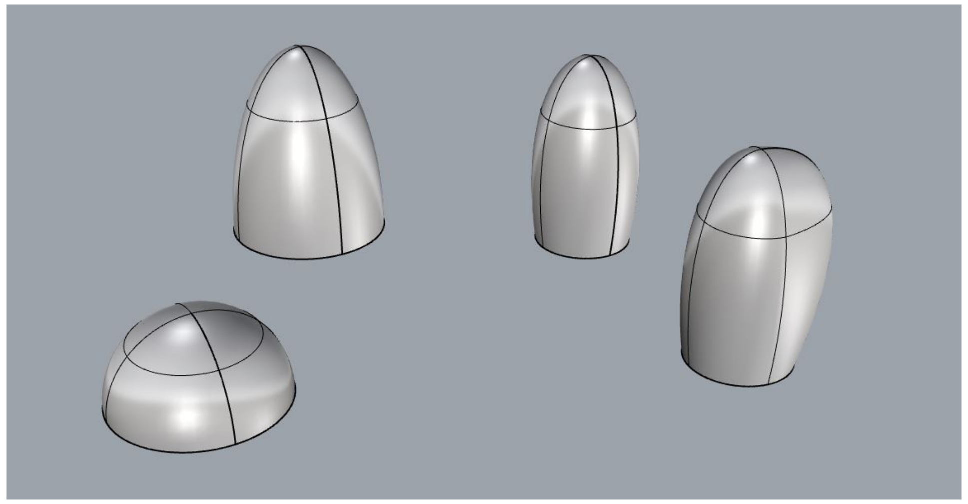
Another factor that influences the size of the module to be used in large-scale applications is the manufacturing limitations. For example, in the case of 3D printed manufacturing, the size of the bedplate of the printer would determine the maximum possible dimensions for the voxel.

Geographical conditions

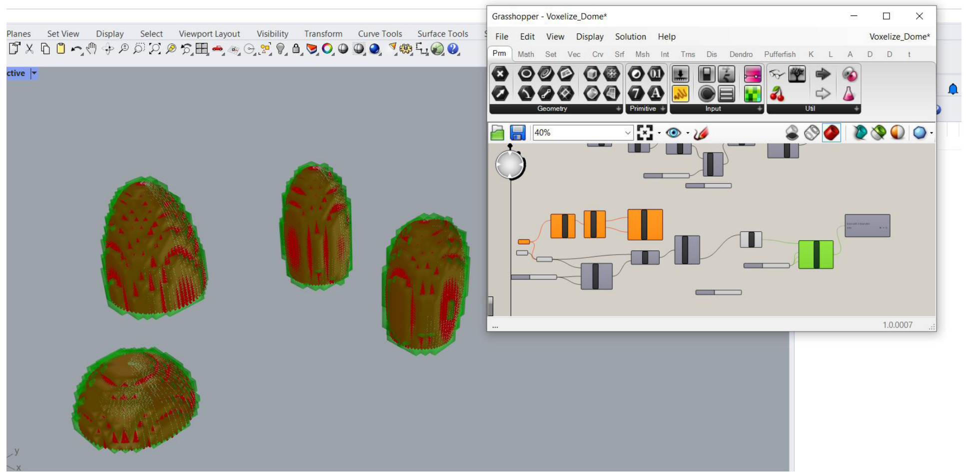
After discussing the concept with experts in relevant fields, it was discovered that the geographic location for the application also influences the decisions for scaling the module size. In the case of the Netherlands, due to the type of Dutch soil, the foundation for such structures needs to be specifically planned considering both the soil type and the module size Thus, to sum up, all these factors need to be collectively considered to determine the size of a module of the lattice structure for a specific application. And accordingly, the submodules can be manufactured and packaged. The manufacturing process also involves an additional step to be performed before packaging. The submodules if manufactured from metal or similar material then need to be tapped for interconnection. And if the submodule is made from plastic-type material then adding a metallic insert(or nut) to the hole is needed before packaging. The lightweight characteristic of the lattice structures and the modular design make it easier to stack these submodules into compact space and transport it easily to the desired location. The sub-modules are so designed to be able to pile up one over the other and form a cluster of submodules. Figure 37 shows how six submodules that when assembled form a complete module can be stacked together.

Appendix [F] Voxelized Structures

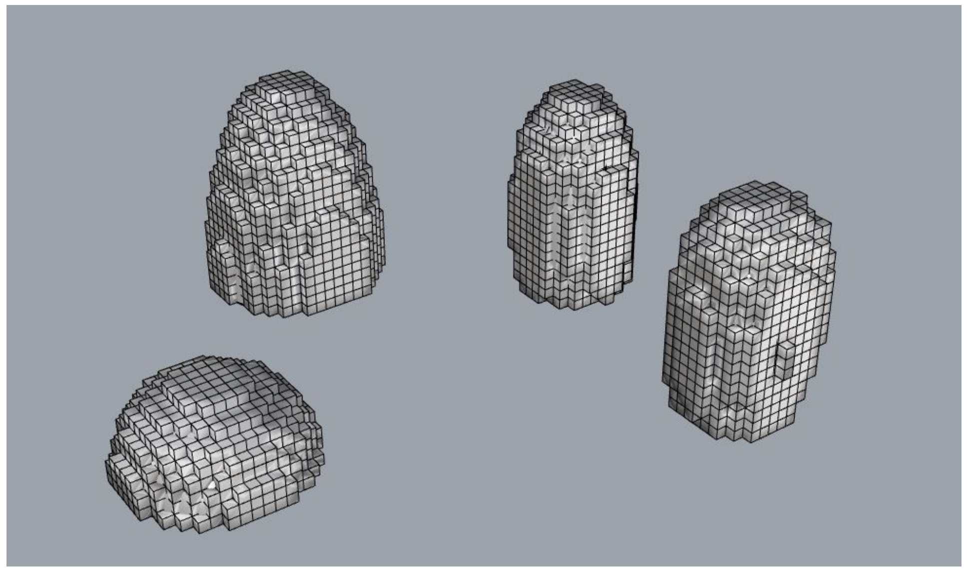
Step 1



Step 2



Step 3



To make use of the robot-material system, an input has to be given to the system such that it knows what to build and how. This is where the designers and architects come into play. Together, they would develop new types of structures that need to be built in these harsh and remote environments, as can be seen in Step 1. Still, these shapes should be transformed into a structure made out of voxels such that the system can build them. Therefore, a small Grasshopper program is written, depicted in Step 2, that can voxelize these shapes. This program needs the initial shapes and voxel size as an input to generate the desired output, seen in Step 3. These voxelized shapes can be used as an input for the robot-material system, where it would decide which voxel to place and where.

Appendix [G]   Arduino Code

```
#include <Wire.h>
#include <Adafruit_PWMServoDriver.h>

// called this way, it uses the default address 0x40
Adafruit_PWMServoDriver pwm = Adafruit_PWMServoDriver(0x7f);
// you can also call it with a different address you want
//Adafruit_PWMServoDriver pwm = Adafruit_PWMServoDriver(0x41);
// you can also call it with a different address and I2C interface
//Adafruit_PWMServoDriver pwm = Adafruit_PWMServoDriver(0x40, Wire);

// Depending on your servo make, the pulse width min and max may vary, you
// want these to be as small/large as possible without hitting the hard stop
// for max range. You'll have to tweak them as necessary to match the servos you
// have!
#define SERVOMIN1  130 // This is the 'minimum' pulse length count (out of 4096)
#define SERVOMAX1  325 // This is the 'maximum' pulse length count (out of 4096)
#define SERVOMIN2  150 // This is the 'minimum' pulse length count (out of 4096)
#define SERVOMAX2  275 // This is the 'maximum' pulse length count (out of 4096)
#define USMIN  600 // This is the rounded 'minimum' microsecond length based on the minimum
pulse of 150
#define USMAX  2400 // This is the rounded 'maximum' microsecond length based on the maxi-
mum pulse of 600
#define SERVO_FREQ 50 // Analog servos run at ~50 Hz updates


String mov;
const int M1A = 5;//define pin 2 for A1A
const int M1B = 6;//define pin 3 for A1B

const int M2A = 9;//define pin 2 for A1A
const int M2B = 10;//define pin 3 for A1B

void setup() {
  Serial.begin(9600);
  Serial.println("8 channel Servo test!");
  Serial.println("Provide action: down, up, rotate90, rotate-90, attract1, repel1, attract2, repel2 grab,
release");
  pinMode(M1A, OUTPUT);
  pinMode(M1B, OUTPUT);
  pwm.begin();

  pwm.setOscillatorFrequency(27000000);
  pwm.setPWMFreq(SERVO_FREQ);  // Analog servos run at ~50 Hz updates

  delay(10);
}

// You can use this function if you'd like to set the pulse length in seconds
// e.g. setServoPulse(0, 0.001) is a ~1 millisecond pulse width. It's not precise!
```

```
void setServoPulse(uint8_t n, double pulse) {
  double pulselength;

  pulselength = 1000000;   // 1,000,000 us per second
  pulselength /= SERVO_FREQ;   // Analog servos run at ~60 Hz updates
  Serial.print(pulselength); Serial.println(" us per period");
  pulselength /= 4096;  // 12 bits of resolution
  Serial.print(pulselength); Serial.println(" us per bit");
  pulse *= 1000000;  // convert input seconds to us
  pulse /= pulselength;
  Serial.println(pulse);
  pwm.setPWM(n, 0, pulse);
}

//Function with input sides to lock
template <size_t N> void lock( int (&TheArray)[N]) {
  int prev = 1;
  int len = sizeof(TheArray) / sizeof(TheArray[0]);
  Serial.print(len);

  //move down
  pwm.setPWM(3, 0, 400);
  delay(2270);


  pwm.setPWM(3, 0, 512);
  delay(2000);


  for (int i = 1; i <= len; i++) {

    if (i == 1) {
      digitalWrite(M1A, LOW);
      digitalWrite(M1B, HIGH);
      delay(1500);

      digitalWrite(M1A, LOW);
      digitalWrite(M1B, LOW);
      prev = 1;

    }

    if (i == 2) {
      Serial.println("2 active");
      pwm.setPWM(2, 0, 210);
      delay(500);

      pwm.setPWM(2, 0, 512);
      delay(2000);



      digitalWrite(M2A, HIGH);
```



```
      digitalWrite(M2B, LOW);
      delay(1500);

      digitalWrite(M2A, LOW);
      digitalWrite(M2B, LOW);
      prev = 2;
    }

    if (i == 3) {

      if (prev % 2 == 1) {
        digitalWrite(M1A, HIGH);
        digitalWrite(M1B, LOW);
        delay(1500);

        digitalWrite(M1A, LOW);
        digitalWrite(M1B, LOW);
      }

      if (prev % 2 == 0) {
        pwm.setPWM(2, 0, 350);
        Serial.write("rotating to -90");
        delay(500);

        pwm.setPWM(2, 0, 512);
        delay(2000);

        digitalWrite(M1A, HIGH);
        digitalWrite(M1B, LOW);
        delay(1500);

        digitalWrite(M1A, LOW);
        digitalWrite(M1B, LOW);
      }

      prev = 3;
    }




    if (i == 4) {

      if (prev % 2 == 1) {
        //rotate 90 deg
        pwm.setPWM(2, 0, 215);
        delay(500);

        pwm.setPWM(2, 0, 512);
        delay(2000);

        ;
```

```
      digitalWrite(M1A, HIGH);
      digitalWrite(M1B, LOW);
      delay(1500);

      digitalWrite(M1A, LOW);
      digitalWrite(M1B, LOW);

    }

    if (prev % 2 == 0) {

      digitalWrite(M1A, HIGH);
      digitalWrite(M1B, LOW);
      delay(1500);

      digitalWrite(M1A, LOW);
      digitalWrite(M1B, LOW);

    }

    prev = 4;
  }



 }



 //rotate back to initial orientation
 pwm.setPWM(2, 0, 350);
 Serial.write("rotating to -90");
 delay(500);

 pwm.setPWM(2, 0, 512);
 delay(2000);

 //move up
 pwm.setPWM(3, 0, 170);
 delay(2450);

 pwm.setPWM(3, 0, 512);
 delay(2000);


};

void loop() {
 // Drive each servo one at a time using setPWM()
 //Serial.println(servonum);
 pwm.setPWM(3, 0, 512);
 int array1[2] = {1,2}; //Sides to lock
```



```
if (Serial.available()) {
 mov = Serial.readStringUntil('\n');
 //Serial.print("You typed: " );
 Serial.println("action: " + mov);

 //Grabs a voxel if grippers are provided
 if (mov == "grab") {
   for (uint16_t pulselen = SERVOMIN1; pulselen < SERVOMAX1; pulselen++) {
     pwm.setPWM(4, 0, pulselen);
   }

   for (uint16_t pulselen = 370; pulselen > 150; pulselen--) {

     pwm.setPWM(5, 0, pulselen);
   }

   delay(2000);

 }

 //Releases a voxel if grippers are provided
 if (mov == "release") {

   for (uint16_t pulselen = SERVOMAX1; pulselen > SERVOMIN1; pulselen--) {
     pwm.setPWM(4, 0, pulselen);
   }
   for (uint16_t pulselen = 100; pulselen < 370; pulselen++) {

     pwm.setPWM(5, 0, pulselen);
   }


   delay(2000);

 }

 //Moves the electromagnet holder down
 if (mov == "down") {
   pwm.setPWM(3, 0, 400);
   delay(2270);


   pwm.setPWM(3, 0, 512);
   delay(2000);

 }

 //Moves the electromagnet holder up
 if (mov == "up") {
   pwm.setPWM(3, 0, 170);
   delay(2450);
```

```
  pwm.setPWM(3, 0, 512);
  delay(2000);

};

//Rotate the electromagnet 90 degree clockwise
if (mov == "rotate90") {
  //for (uint16_t pulselen = SERVOMIN1; pulselen < SERVOMAX1; pulselen++) {
  //pwm.setPWM(3, 0, 325);

  //}
  pwm.setPWM(2, 0, 215);
  delay(500);

  pwm.setPWM(2, 0, 512);
  delay(2000);

}

//Rotate the electromagnet 90 degree counter clockwise
if (mov == "rotate-90") {
  //     for (uint16_t pulselen = SERVOMAX1; pulselen > SERVOMIN1; pulselen--) {
  //     pwm.setPWM(3, 0, pulselen);
  //   }

  //     pwm.setPWM(2, 0, 130);
  pwm.setPWM(2, 0, 350);
  Serial.write("rotating to -90");
  delay(500);

  pwm.setPWM(2, 0, 512);
  delay(2000);

}

//Set electromagnet 1 in repel mode
if (mov == "repel1") {
  digitalWrite(M1A, LOW);
  digitalWrite(M1B, HIGH);
  delay(1500);

  digitalWrite(M1A, LOW);
  digitalWrite(M1B, LOW);

}

//Set electromagnet 1 in attract mode
if (mov == "attract1") {
  digitalWrite(M1A, HIGH);
  digitalWrite(M1B, LOW);
  delay(1500);
```



```
  digitalWrite(M1A, LOW);
  digitalWrite(M1B, LOW);

}

 //Set electromagnet 2 in attract mode
if (mov == "attract2") {
  digitalWrite(M2A, LOW);
  digitalWrite(M2B, HIGH);
  delay(1500);

  digitalWrite(M2A, LOW);
  digitalWrite(M2B, LOW);

}

//Set electromagnet 2 in repel mode
if (mov == "repel2") {
  digitalWrite(M2A, HIGH);
  digitalWrite(M2B, LOW);
  delay(1500);

  digitalWrite(M2A, LOW);
  digitalWrite(M2B, LOW);

}

//Activate lock function and will perform all the right movements to lock the desired sides.
if (mov == "loc") {
  lock(array1);

}



 }
}
```