Design of cellular structures for robotic assembly

MSc Integrated Product Design
Graduation Thesis

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Abstract

We explain the design and analysis of a novel voxel design with the goal of reducing assembly time and complexity of the robot-material system. Recent advances in robot-material systems, on the other hand, have focused on mechanical properties, design, and production methods. Making it possible to create cellular structures in harsh and remote environments. These systems, which are built up of voxels and small mobile robots that live on top of the structure and move the cellular structures, nevertheless lack a connecting mechanism that reduces total system complexity and assembly time to a level that is desirable to people.

The design of these voxels prioritizes ease of assembly through simple actuation and is investigated by proposing a method to connect voxels via an end effector without removing mechanical qualities while maintaining the system's modularity principle. Modularity is a design idea that divides a structure into smaller sections called voxels that can be built and assembled separately to build the required structure. Simultaneously, the end effector's design aims to connect a voxel with the fewest degrees of freedom possible, while also holding a voxel throughout transit and placing the voxel in the desired spot.

A new connection mechanism for cuboctahedral cellular structures was devised, which would enable the building of required large-scale structures faster and easier. Several prototypes and experiments were used in the design of this connection mechanism. The final prototype was built by fused deposition modeling and demonstrated by attaching the end effector to a Universal Robot 5 (UR5) and completing a series of movements to simulate the autonomous assembly of a bridge. The concept evaluation resulted in an end effector that can connect all sides of the voxel with only two movements, without requiring the robot to go around the voxel. This idea lays the groundwork for enhancing the way robots form cellular structures and creating a mechanism to make them more appealing to humans when exploring remote settings. The study finishes with future research opportunities and prospective applications of such a connection mechanism in robot-material systems.

Acknowledgement

First and foremost, I'd want to thank my supervisors, Dr. Jun Wu, Dr. Kunal Masania, and Ir. Eric Garner, for providing me with this opportunity and actively guiding me throughout my graduation project at the TU Delft's Faculty of Industrial Design Engineering. They kept me on track throughout the project's timeframe and were instrumental in steering me in the proper direction. Expert guidance and supporting encouragement were both crucial in completing this assignment on time with an unique conclusion.

I'd like to thank Joris van Dam, a lab technician at the Applied Labs, Faculty of Industrial Design Engineering, in addition to my supervisors. With his robotics knowledge, he assisted me during the development stage and prototype test setup. I would like to express my gratitude to Dr. Rob Bernardus Nicolaas Scharff and Ir. Alex Luijten for advising me on the use of soft and stiff robotics in this design for the connecting mechanism. I am grateful to MSc. Guille Presa Magriña of the TU Delft Faculty of Aerospace Engineering for assisting me with the design process and sharing insights from his part of the project. I am grateful to Bent Verhoeff for being there throughout the project, as well as to my colleagues designers and friends who assisted me throughout the project through co-creation sessions, brainstorming meetings, and constructive criticism. Last but not least, I am grateful to my parents and Loïs Andrews for their ongoing encouragement and support.

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01 Introduction

Because of its numerous advantages, cellular structures have long been favored in the field of design engineering. The key reason for this is its capacity to construct various structures using the same similar construction blocks (voxels). Cellular structures are things that are periodic in nature, consisting of continually repeating unit cells that interact in three dimensions. These structures are a new approach to reducing weight, energy, and advanced production time (Helou, M., & Kara, S., 2017).

Modern engineering solutions rely heavily on lightweight constructions. Lowering structural bulk while enhancing system performance results in improved overall efficiency. Operating costs can be cut while resources are retained. Lighter constructions reduce fuel use in transportation, aiding in the fight against climate change. (Luijten, A., 2020) Manual assembly of cellular structures, which is time-consuming, is currently the sole option for assembly. This can be solved by employing repeated unit cells. It produces a framework that is easily navigable by small mobile robots. The cell's geometry can provide great packing efficiency, reducing wasted payload space while maximizing structural performance and constructibility (Ochalek, M., 2019).

NASA came up with the notion of creating assembler robots while researching cellular architectures for reconfigurable space structures (Ochalek, M., 2019). This system is primarily intended for high-performance structures in severe conditions. The plan is to launch an army of tiny robots into orbit, along with a slew of building bricks. These armies will construct and maintain constructions on space stations or celestial bodies, as seen in Figure 1.

These structures will only be useful if the manufacturing and assembly processes can be automated. As a result, this research will investigate the links between the various subsystems in order to build an integrated robot-material system. Because the current system can only travel around the structure and insert a voxel in a rotational fashion, the systems still lack a connection between the voxels, a end effector to do so, and an enhancement in the voxel design to simplify path planning and voxel setup.

This study will focus on the development of a good robot-material system. As a result, the robot can effortlessly create, remove, and repair cellular structures without jeopardizing their benefits. In addition, sustainability must be considered. Gawde's study kicked off this concept by creating a modular unit cell (Gawde, P. R., 2021). This project will be utilized to further develop the system in a sustainable way so that it may be used more widely on Earth.

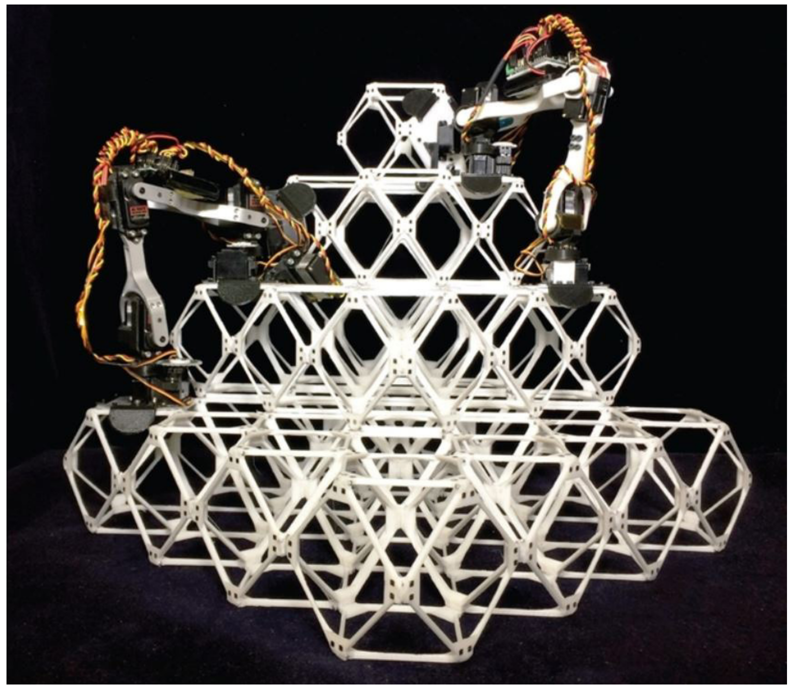


Figure 1. Mobile robots which assemble a discrete cellular structure (Jenett, B., 2019)

1.1 Assignment

Currently, there are sufficient studies about cellular structures, but only a few about robot assemblers and the integration of the assembly robot with cellular structures. In the studies about the integration most voxels shapes are different from Gawde'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. 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. Another constraint is that the robot only works in a controlled environment, and not yet in a dynamic environment.

These limitations show us that there is still no success in the developing of a robot-material system consisting of mobile robots which can assemble, the previously designed voxels by Gawde. 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.

I will design and create an connection method based on its corresponding building blocks to efficiently assemble cellular structures in a controlled environment.

1.2 Process

The research by design methodology was used in conjunction with the double diamond method during the project (Figure 2). It is primarily goal-oriented rather than process-oriented. This report is recorded to highlight the entire procedure that was followed as well as the knowledge gained throughout the project. Given the assignment, the first step is to extend the perspective by researching related work and then applying this knowledge to begin designing and testing. Collect data, update it, and conduct additional study on the questions raised during testing.

First, use the information to construct an issue description based on the above research study's analysis and findings. The possibilities for developing an integrated robot-material system are then investigated. Understanding how the system works and what needs to be changed will be aided by ideating and quickly prototyping voxels and their connectivity. This resulted in the creation of the end effector for connecting the voxels. The connection mechanism of the robot-material system are demonstrated, and the work's learnings are ended with potential future developments.

1.3 Scope

Given the time and budget constraints, the project's primary goal was to investigate the impact of creating a connecting mechanism in order to achieve a simple and sustainable overall system. As a result, the investigated cellular structure and concept(s) are limited to the cuboctahedron as a voxel, which will be employed as the initial unit cell. Furthermore, dealing with the intricacies of numerous dynamic loads and Finite Element Analysis (FEA) in relation to the exhibited application is considered to be beyond the scope of the demonstration.

Also, as previously indicated, this project is a continuation of Pranav Gawde's work, therefore the study on the relevance of repair in a circular economy and the sustainability impact due to repairability is not carried out independently but is incorporated into the prior work. This research looked specifically at how to create a robot-material system capable of efficiently building cellular structures in a controlled environment.

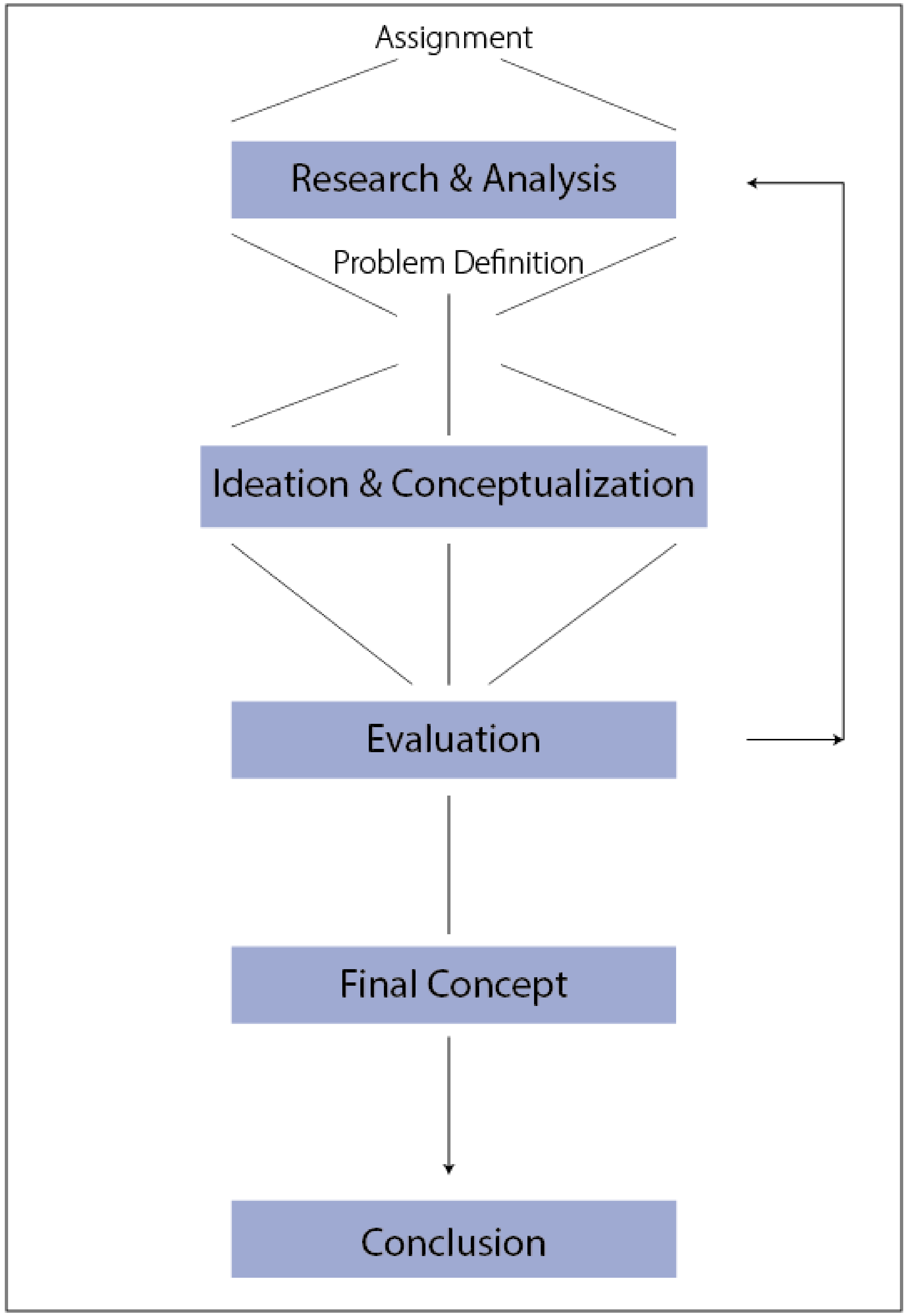


Figure 2. Illustrator of the design methodology used during this project

02 Research & Analysis

The research phase includes a review of current literature on assembly robots, robot-material systems, and connection techniques. These results were then reviewed in order to develop a specific design goal as well as the program of requirements for establishing a robot-material system. Several judgments made based on a growing understanding of the relevant work directed further literature investigation and analysis of similar work done and/or presently in process.

2.1 Objectives and Method

The goal of the literature review was to first widen the known knowledge regarding robot-material systems, then assess the obtained content and eventually answer the following research questions, which were formed as the research phase advanced. The responses to these questions aided in the development of a more focused problem statement, which will be concepted, analyzed, and tested in later stages of the project. The strategy used to access the relevant material was to conduct a search on Google Scholar using keywords and then snowball.

1. **What are robot-material systems?**
2. **How are voxels connected to each other?**
3. **How does the shape of a voxel influences the overall system?**
4. **What does sustainability means in a robot-material system?**

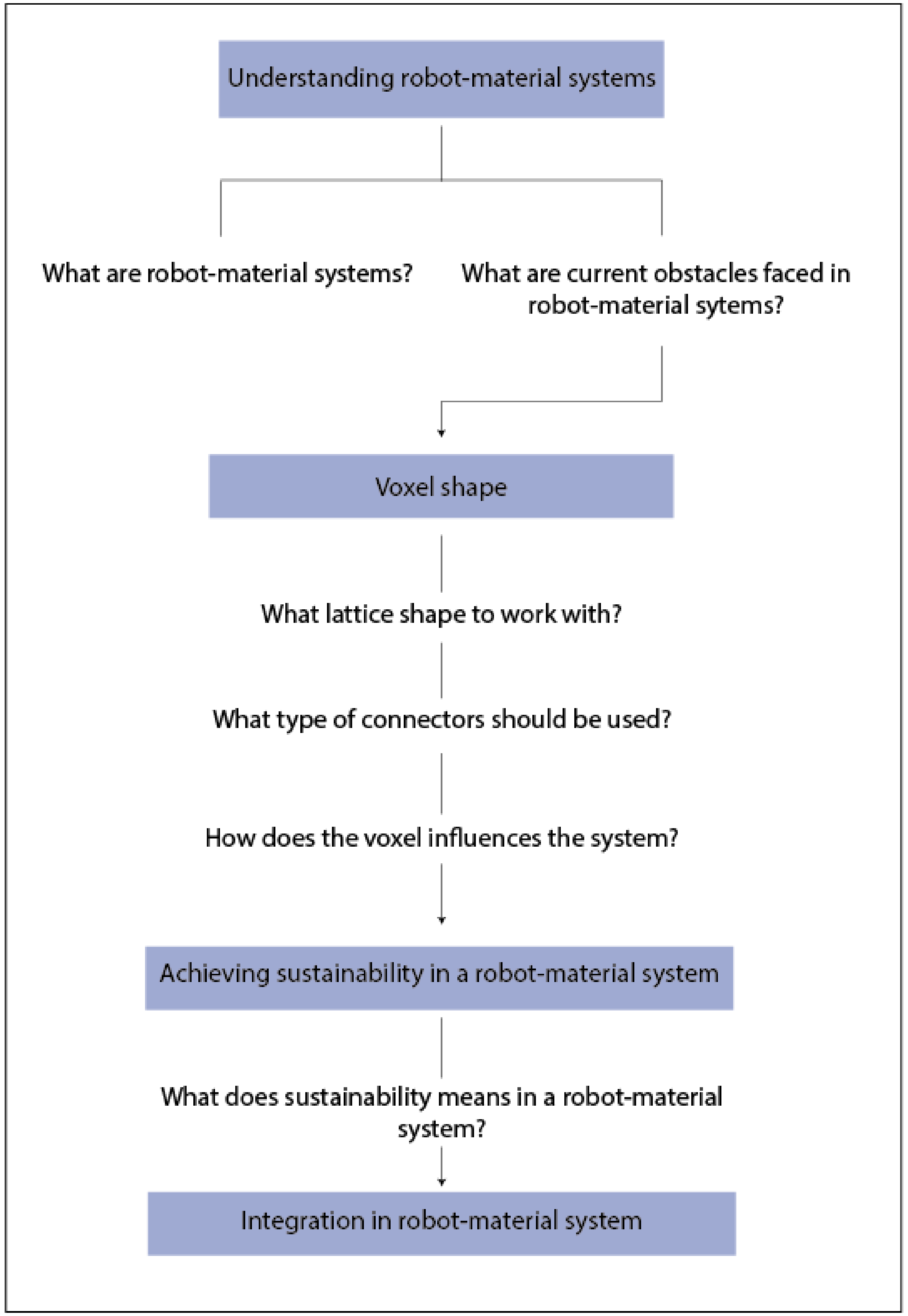


Figure 3. Illustrator of the direction followed during the research phase

2.2.1 Understanding robot-material systems

What are robot-material systems?

The terminology "robot-material system" refers to the symbiotic relationship that exists between the robot and the material utilized to construct discrete cellular structures. The robot resides on the structure in order to assemble, disassemble, and maintain it. As a result, the structure benefits from the robots, allowing it to maintain its performance and structural integrity. Nonetheless, the robot benefits from the structure because of the utilization of identical voxels, which results in a robot design that is relative to and coordinated with the cellular structure. Making the robot's voxel setup and path planning simpler (Jenett, B., 2019).

These systems' materials are known as discrete materials, which are derived from discrete manufacturing. The manufacturing of finished products (voxels) that are distinct items capable of being easily counted, touched or seen (O'Donnell, J., 2017).

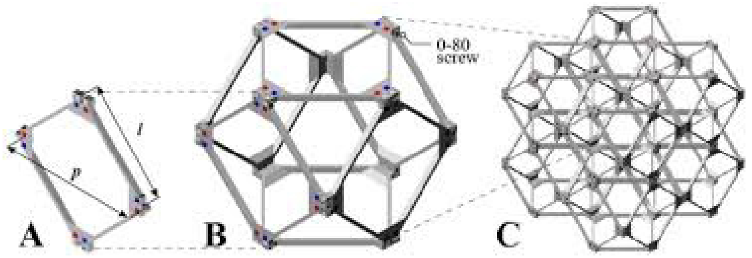


Figure 4. Discrete cellular material system. A) Submodule B) Voxel C) Lattice structure (Jenett, B., 2019)

On the other hand, a new sort of robot known as a "relative robot" has been designed. Relative robots are an exciting new addition to the field of high-performance cellular structures. According to Jenett, relative robots are task-specific platforms that are developed relative to a certain spatial environment and are used for simplicity and implementation (Jenett, B. & Cellucci, D., 2017).
Previously, there were two major categories of robotics: those made of pricey custom components that were precisely optimized for specific purposes such as factory assembly, and those made of inexpensive mass-produced modules with substantially inferior performance. This new system results in the creation of a new sort of robot. It is, however, an option to both. They are significantly simpler than the former but far more capable than the latter, and they have the potential to change the creation of large-scale systems ranging from airplanes to bridges to entire buildings (Chandler, D. L., 2019).

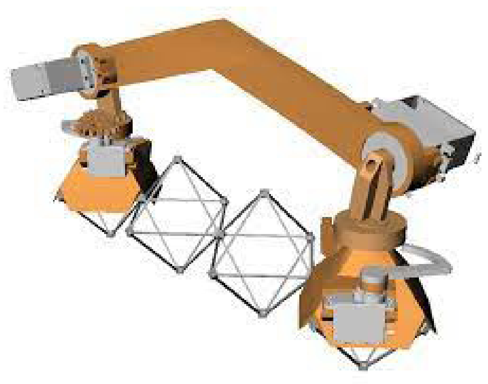


Figure 5. Artistic visual of BILL-E robot (Jenett, B., & Cheung, K., 2017)

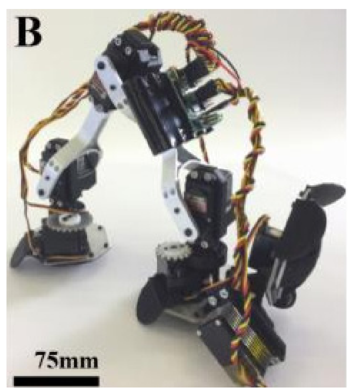


Figure 6. Build up relative robot (Jenett, B., 2019)

What are the current obstacles faced in such robot-material systems?

The present versions of robot-material systems have various shortcomings that must be addressed. The system still need improvements in structural performance, scaling, and controls. Aside from that, the system's voxels should be updated in terms of their joint and constituent materials. Furthermore, the voxels are linked by magnets, which cannot be employed as structural links but may be sufficient for voxel alignment. The low-fidelity 3D printed material has proven to be effective in prototyping, but it will require modification when this system is employed in real-world scenarios. Jennet has made a material suggestion, proposing to replace it with injection molded GFRP, which has been proved to offer low cost and great performance at comparable scales (Jennet, B., 2019).

The design of the robot itself also has some issues when locomoting vertically due to gravity but the scale of the robot is then as well limited by the voxels and components used. The lower scale limit is driven by the external dimensions of the commercial-off-the-shelf (COTS) components like the actuators which are needed for movements of the robot. The upper scale limit is driven by the torque density of the COTS components which are not linked to the up scaling of the robots and the components used (Jennet, B., 2019).

Finally, the end effector on the robot will need to be completely redesigned. The present version of the end effector can only pick up and insert a voxel by rotating it around a specific axis. As a result, the end effector cannot pick up or position the voxel in-between voxels, resulting in more complex path planning and voxel setup. In addition, the end effector should be able to (dis)connect voxels, which is still being designed. This will be controlled mostly by the interconnection system and the voxel shape (Jennet, B., 2017).

2.2.2 Voxel shape

What cellular shape to work with?

Previous research on robot-material systems has looked at various cellular structures that could be used as a starting point for this system. A NASA study team conducted the main comparison of the best voxel units for large-scale local or relative reference robotic assembly. Figure 6 depicts the results of a study that compared six distinct unit blocks (Ochalek, M., 2019).

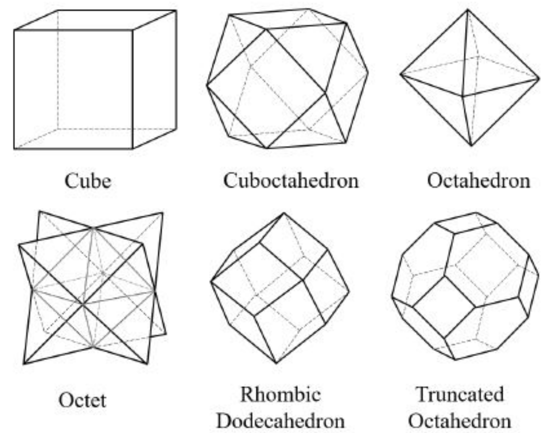


Figure 7. Unit blocks (Ochalek, M., 2019)

Table 1: Chosen parameters for deciding on voxel shape (Ochalek, M., 2019)

Independant properties	dependant properties
Number of attachment per voxel	Stiffness scaling
Number of attachment per adjacency	Strenght scaling
Coefficient of volume	Tiling
Average number of attachments per coefficient of volume	Packing efficiency
	Volume allowance for robotic end-effector
	Strut clearance angle

Each one of them is graded on different parameters to create an as simple robot-material system. These parameters can be found in Table 1 and are explained in appendix B.

Most importantly, consider the complexity it adds to the assembly robot's path planning, locomotion, and voxel setup when deciding on which unit cell to utilize. The selection method was preceded by an elimination process, which determined the best geometry. All geometries that matched the minimal structural performance criteria were chosen first. Following that, it is examined which tiling patterns add complexity to the robot's movement, which geometries have no strut interference, zero volume for end effector permission, and a large number of attachments. All of these are deleted, leaving only the cuboctahedron, whose value is that having a moment resistant structure from just one additional unit cell considerably decreases the system's overall locomotion and path planning needs.

Another study on robot material systems by Luijten (Luijten, A., 2020) use octahedrons rather than cuboctahedrons for the simple reason that an older work by NASA employs the same unit cells. In addition, he modified the voxels such that they could be easily 3D printed and combined. This allowed for the creation of ultra-lightweight voxels weighing less than 10 mg/cm3.

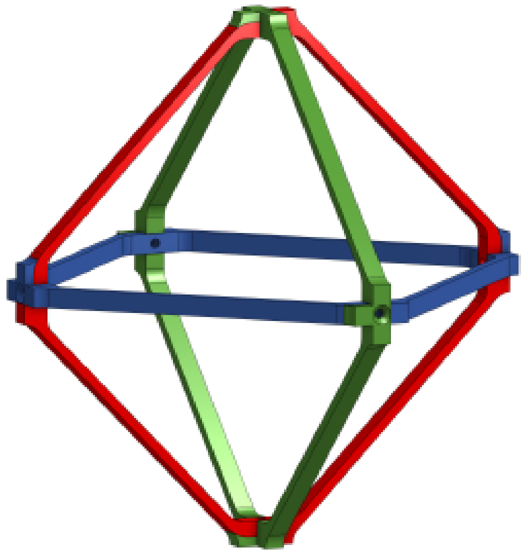


Figure 8. Voxel shape by Luijten (Luijten, A., 2020)

The only issue is that there is only one attachment point, which reduces load transfers and allows the voxel to rotate. The inclusion of bolts and nuts as connections, as well as the choice of voxel type, adds to the complexity of path planning and voxel setup (Ochalek, M., 2019).

Finally, Gawde investigated the modularity of such unit cells and chose cuboctahedrons as voxels for large scale cellular constructions. His judgment comes from a study of strut and node-based, face type, and 3D unit cells as voxels. During this comparison, he focused on the ease of producing and assembling such voxels. He arrived at the conclusion that the face type voxel or cuboctahedron would be used as a building block in cellular architectures through elimination (Gawde, P. R., 2021).

The benefits of choosing a unique square face sub-module with pegs and dowels at alternate corners for intraconnection resolved various challenges observed in the other cases:

1. The manufacturing of these sub-modules was convenient due to no need for any supports for 3D printing
2. No/fewer inefficiencies in the printed part due to the absence of any complex geometry. Saving the time for post-processing the submodules
3. Self interlocking intraconnections i.e. pegs and dowels, limiting the use of any external or additional fasteners only for the interconnection.

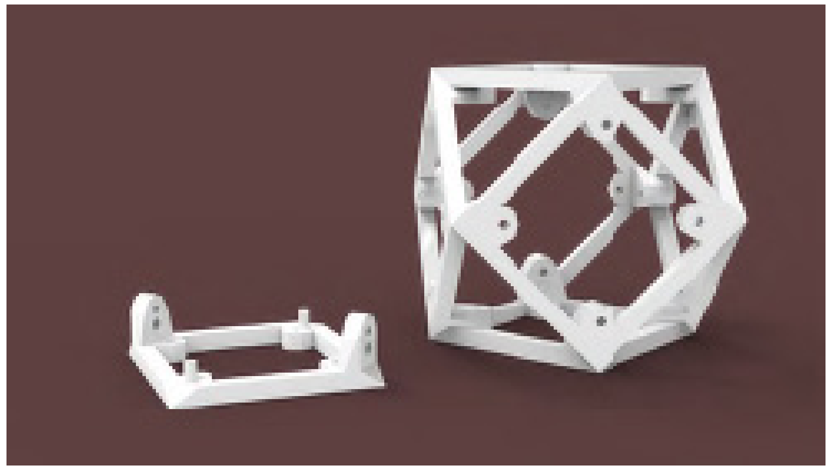
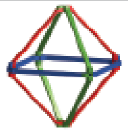
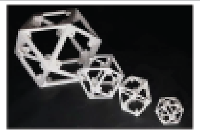


Figure 9. Voxel shape by Gawde (Gawde, P. R., 2021)

To pick which geometry to employ as the beginning point of this study, I opted to compare both geometries used by Luijten and Gawde with the knowledge gathered through NASA's comparison. I compared the characteristics that thought to be important in Table 2 .

This comparison clearly shows that the octahedron has better mechanical qualities, is easier to construct, and falls into the ultra light-weight structure category, making it less expensive to transport. However, if NASA's evaluation of complexity in path planning and locomotion is taken into account, these can be stated to be more essential than structural features. Furthermore, Gawde's cuboctahedron is simple to build and assemble, making it easier to prototype and test. Finally, the cuboctahedron offers greater load transfer than the octahedron due to its flat faces and numerous vertices linked. For these reasons, it was agreed that the geometry for the beginning of this project would be Gawde's cuboctahedron.

Table 2. Comparison between the octahedron and cuboctahedron

octahedron 	**Cuboctahedron** 
Stretch dominated	Bending dominated as well as stretch dominated to some extend
2D faces: easy to manufacture with 3D printing	3D faces: easy to manufacture with 3D printing
vertex connection: one point of connection between two voxels	face connection: four points of connection between two voxels
Weight: < 10mg/cm^3	Weight: 35g
Parts to manufacture: 3	Parts to manufacture: 6
Mechanical properties: Performs well under axial compression	Mechanical properties: Performs wors under axial compression
Increases complexity in path planning and voxel configuration	Reduces complexity in path planning and voxel configuration

What type of connectors should be used?

Currently, the voxels are aligned with magnets, which cannot be used as structural connectors since they drop when a load is put to the structure's top. This prompted us to investigate various sorts of connection mechanisms that can be readily secured and unfastened by robots.

The first and most obvious connector is to use bolts and nuts. An idea shared by Gawde and Luijten. The downsides to the technique are that when we utilize 3D printing as a production process, we must include inserts during the print. The robot can only carry a limited amount of bolts during installation and can only be loosened from one side, making voxel setup and (dis) assembly more difficult. This increases the complexity of the end effector because it must enter the voxel, align with the connection point, and be able to fasten two voxels.

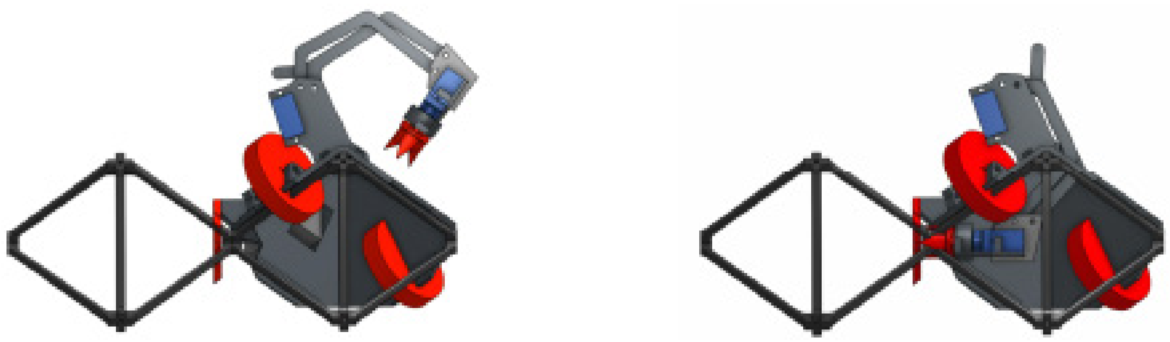


Figure 10. Robot end effector by Luijten. (L) Initial position (R) Connection position (Luijten, A., 2020)

Luijten 's solution is shown in Figure 1, however because this project would employ a cuboctahedron as a voxel, this method would become much more complex because it would now need to connect four points instead of one (Luijten, A., 2020).

Tool-less interconnections, such as the dovetail and bayonet, are another sort of connection mechanism considered. The dovetail is well-known for its tensile strength and is made up of a male and female component (Klosowski, P., 2019). Some issues arise during the building of cellular systems due to the presence of male and female pieces. First and foremost, due to the utilization of male and female submodules, unity will be lost. Furthermore, it will enhance the complexity of path planning and voxel arrangement. Finally, it is possible that the male component will protrude from the structure, disrupting the aesthetics, and that something can entangle with the framework.

The bayonet, on the other hand, has an advantage over the dovetail since it is androgyneous. Androgynous fasteners are those that have two identical pieces. Both portions function as male and female parts, making it easy to build and (dis)connect objects from opposing sides (Ren, J., 2021). However, because the bayonet has a lesser tensile strength than this dovetail, it should be included into the voxels, increasing the complexity of the end effector due to the increased DOF.

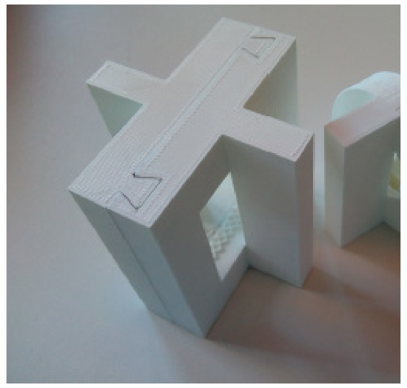


Figure 11. Dovetail design (Ornstein, O., 2022)

Figure 12. Bayonet design (Ornstein, O., 2022)

NASA is currently developing androgynous fasteners for use in robot-material systems to create cellular structures (Formoso, O., 2020). During the prototyping course, Tudelft students examined these fasteners. The design is appealing to them because of its mechanical qualities, ease of (dis) assembly, and incorporation of the advantages of the dovetail and bayonet designs. The primary issue to be addressed is the manufacturing method, which is now confined to 3D printing and voxel integration. Nonetheless, this style of fastener has the same constraints as regards to the end effector when using bolts and nuts (Ornstein, O., et all., 2022).

Figure 13. Androgynous fastener design (Formoso, O., 2020)

This is followed by the application of kinematic coupling. Kinematic coupling refers to fittings that are meant to precisely limit the part in question, resulting in precision and certainty of placement (Slocum, A., 2010). As shown in the illustration, the most usual instance is to have one side with slots and the other with balls that fit into these slots. This keeps the two sides from rotating and translating. Only using this again generates different parts, losing modularity. Regardless of whether this is commonly utilized, it can also be another sort of kinematic coupling that puts parts into place by force, making voxel setup as well as structure assembly and disassembly straightforward.

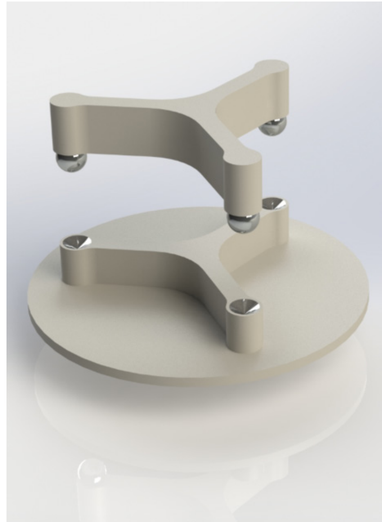


Figure 14. Kinematic coupling mechanism

Finally, the system may employ compliant mechanisms. A compliant mechanism is a flexible mechanism that transmits force and motion by elastic body deformation. Compliant mechanisms are often quite complex, but they are usually built of a single piece and are easy to produce (Jagtap, S. P., 2021).

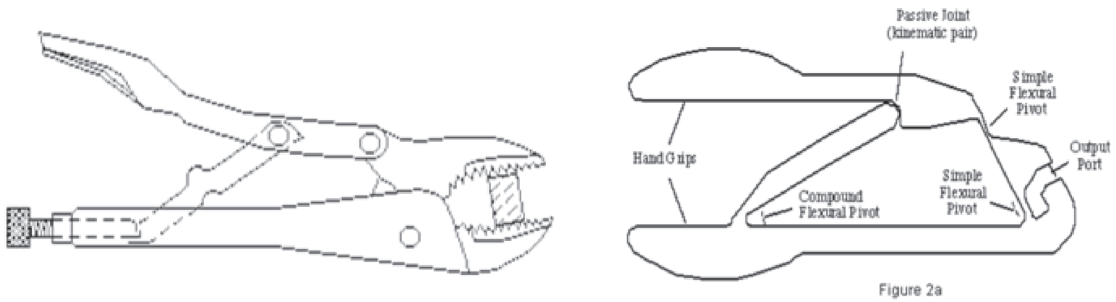


Figure 15. Representation of tool as a compliant mechanism (Plewa, K., 2019)

Taking into account all of the different types of connection systems that have been covered. Because of the complexity they add to the system, it is obvious that bolts and nuts will be deleted. Both androgyneous fasteners should be embedded into the voxels and be capable of being (un) locked from both sides. This would be quite tough, because it adds an extra DOF to the end effector that may or may not be required. During the ideation and conceptualization phases, tool-less fasteners such as dovetail, kinematic coupling, and compliant mechanisms will be investigated in order to compare and develop a new form of fastener for the robot-material system.

How does the voxel influences the system?

Because the system is made up of discrete materials, how it is (dis)assembled and how the robot is constructed will have an impact on the overall system. It is chosen at the start of this part that the cuboctahedron would be utilized as the shape for the voxels, which has an influence. The cellular structure must maintain structural integrity, which it will do through good load transfer. This is accomplished by increasing the surface area of contact between the voxels and the four attachment vertices. By merely adding one more voxel at the end, the flat surface and points of attachment produce a moment-resisting structure, reducing the complexity of path planning and voxel setup. This shape will influence how the cellular structure is built, and when combined with the appropriate type of connecting system, it will reduce total system complexity (Jennet, B., 2019).

The robot, on the other hand, will be designed mostly around the shape of the voxel. Geometry, kinematics, actuation, end effectors, and sensors are all part of the design of a robot system. The robot's geometry and kinematics are based on the maneuvers and configurations required to meet the desired goals of full 3D locomotion, voxel transfer, and placement (Jenett, B., & Cheung, K., 2017).

Jenett's current relative robot is based on the pitch between two consecutive voxels. Figure 15 depicts how pitch connects to the design of the robot and how pitch relates to determining the angles of the robot. With all of the variables known, reversed kinematics can be used to calculate motor angles for positions and motions (Jenett, B., 2019). The following equations can be used to find the corresponding angles:

$$\theta_1 = \tan^{-1} 2(x, y) - \tan^{-1} 2(a_2 \sin\theta_2, a_1 + a_2 \cos\theta_2)$$
$$\theta_2 = 2\tan^{-1}\sqrt{(a_1^2 + a_2^2)^2 - (x^2 + y^2)/(x^2 + y^2) - (a_1^2 + a_2^2)^2}$$
$$\theta_3 = 540° - \theta_1 - \theta_2$$

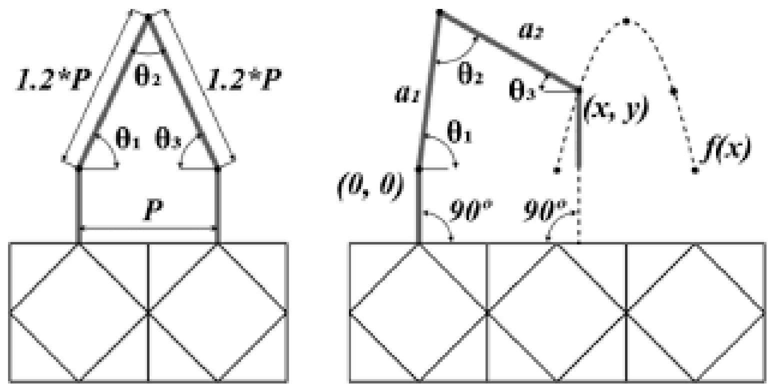


Figure 16. Equations and relation to the robots angles (Jenett, B., 2019)

COTS actuators were chosen to facilitate the robot's rapid development. This was also reflected in the actuation need via calculations and practical considerations. All The end effectors in the current version are the same and rely on the voxel shape to easily locomote, pick up, and position a voxel. Some type of sensing is required for the robot to efficiently construct and locomote on the framework. Two tactile sensors are included in the end effectors to provide input during locomotion.
When both are engaged, the robot can be certain that the foot is properly positioned and that it can lock itself to the voxel. The feedback provided to the robot while placing a voxel is provided by measuring the torque, which will produce a specific torque indicating that the voxel is being

placed or picked up. All of these voxel-influenced concerns make up Jenett's first iteration of the robot, which may be seen in figure 16 .

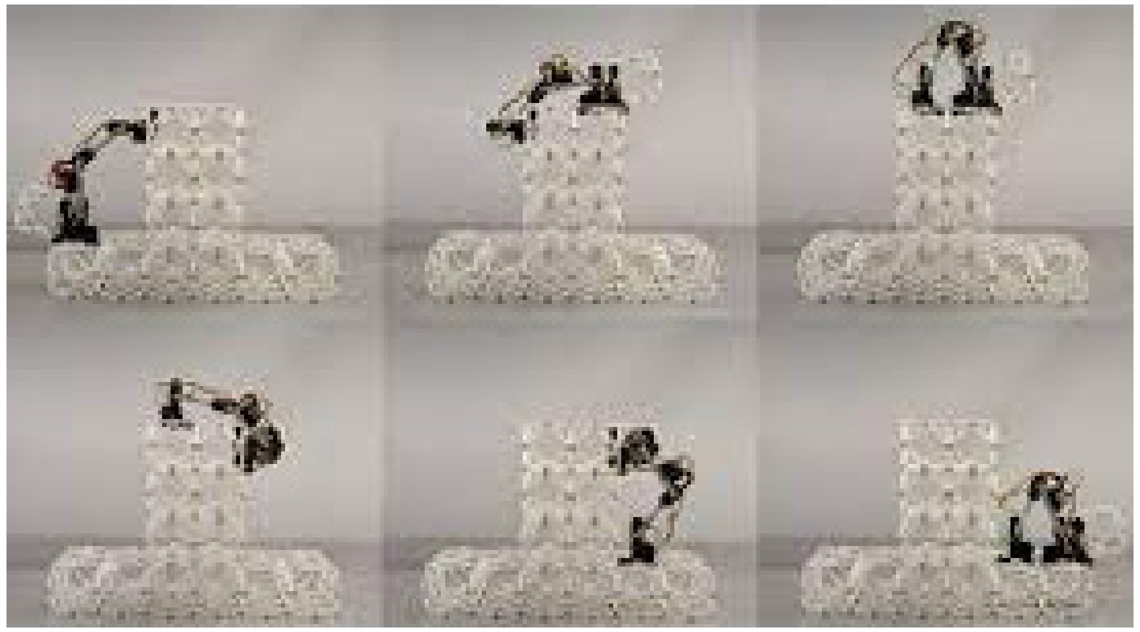


Figure 17. Mobile robot moving over a cellular structure while carrying a voxel (Jenett, B., 2019)

2.2.2 Achieving sustainability in a robot-material system

What does sustainability means in a robot-material system?

There are various levels of sustainability to consider in a robot-material system. First and foremost, the material from which the voxels are produced, how the voxels are constructed, and how the structures are constructed and used. Currently, the substance used for the voxels is PLA, which is created by 3D printing. This facilitates rapid and low-cost prototyping. The use of 3D printing is beneficial since it eliminates production waste, but it has drawbacks in that it can take some time and its structural features may not be adequate in real-world scenarios. It has been suggested that injection molded GFRP be used, which has been proved to provide low cost and great performance at comparable scales (Jenett, B., et all, 2017).

Gawde's submodules build a modular voxel, which makes the system sustainable. Because the submodules are identical, manufacturing is faster and less expensive, and voxels are easier to repair and maintain. More may be done to make the overall system sustainable when looking at the structure as a whole. If the structure itself is modular, the energy required to (dis)assemble, repair, and maintain it would be reduced, making it more sustainable. In addition, the robot itself would be simplified because its difficulties are generated from the amount of moves required to position a voxel. A modular framework would also minimize complexity, resulting in simpler robots that would be easier to replace if one broke down.

Still, it's all about the relationships between the voxels. A voxel should be able to be (dis)connected on its own without the robot having to move around it or (dis)connect other voxels around it. If this is accomplished, which increases reparability and maintainability at the voxel and structural levels.

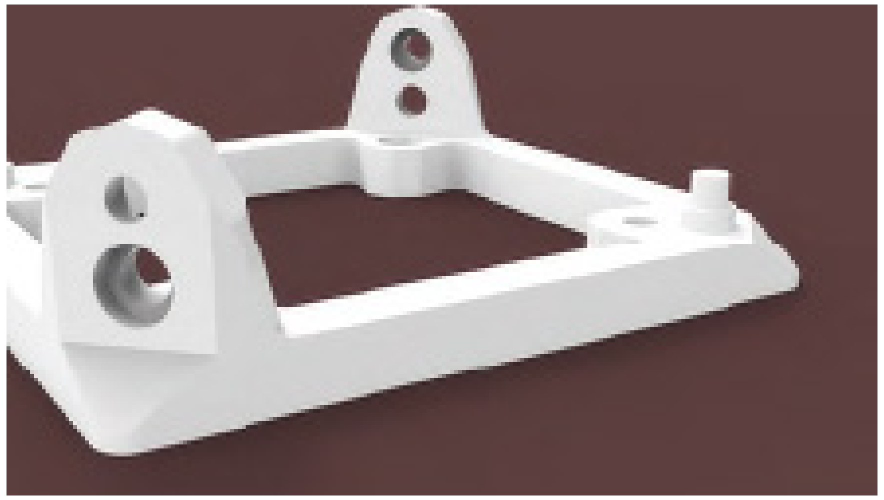


Figure 18. Submodule design by Gawde (Gawde, P. R., 2021)

Table 3. Benefits of reusing (Sherman, R., 2019)

Benefits of Reusing
Save or delay purchasing and disposal costs
Conserves resources
Reduces the waste stream
Causes less pollution than recycling or making new products from virgin materials
Makes needed items available to those who can't afford to buy them new

Aside from all of the integrated pieces, the idea of using the structures for temporary structures and reusing the same voxels is also environmentally friendly. Table 3 shows that the benefits of reuse outweigh those of recycling.

The manner in which the systems are used, as well as their location, can have an impact on their long-term viability. Because these structures are lightweight and have good structural performance, the primary situations for which this system is developed are in the field of aerospace. Eventually, similar methods could be utilized to create entire buildings, especially in harsh conditions like space, the moon, or Mars. This could eliminate the need to transport big preassembled structures from Earth. Instead, enormous amounts of the tiny submodules and an army of assembly robots might be sent. As a result, the first idea is to use the system for dwellings on other celestial bodies because these voxels may be packaged in a compact manner, reducing cargo weight and allowing them to be assembled automatically without human assistance (Chandler, D. L., 2019).

But the question is, what can it be used for here on Earth, and what benefit do we have here? The advantages of these cellular structures are their enormous strength in relation to their material utilization and density. This system is useful in a variety of applications due to its ease of (dis)assembly, reparability, and maintainability. Students in the prototyping course conduct research on a variety of cases. The structures could be used for packaging, bridge construction, shelter construction, or even water management systems. Most importantly, it can be utilized for any form of temporary or permanent structure (Ornstein, O., 2022).

Figure 19. Render of cellular structure used as shelter (Ornstein, O., 2022)

2.3 Takeaways

Robot-material systems, the shape of their voxels, benefits, and limitations, among other things, were investigated and examined. Various decisions were made and as a result the project's direction was established. The following are the key takeaways:

1. The system will employ cuboctahedrons as voxel shapes because the comparison revealed that the octahedron must be discarded. This shape results in a simpler system overall, as demonstrated.

2. A variety of connection systems are explored in terms of their advantages and disadvantages in comparison to the system. As a result, the adoption of kinematic coupling and/or compliant systems as connection systems became a priority.

3. Focus on the design of the robot's end effector.

4. The system is a symbiotic relationship between material and robot. Display and emphasize the robot's integration with the material. As a result, it has been established that the voxel was the starting point for the majority of design decisions.

5. Concentrate on the system's modularity using the cuboctahedron and how the connecting system and robot influence this process.

6. Because they would make the system too complex, the principal use cases in uncontrolled environment are eliminated. As a result, the emphasis will be on use cases in controlled environments.

All takeaways created a way to split up the robot-material system in 6 subsystems that should be considered during this project.

1) The interconnection between voxels

2) The voxel

3) The cellular structure

4) The robot

5) The robot's end effector

6) The system's relation to the environment

All subsystems influence each other, which influences the design decisions taken during this project. Understanding these relationships will aid in the creation of an efficient design process as well as provide a general notion of what this system should look like. The relationships are depicted in Figure 19 and explored further below.

The voxel will have an effect on the main relationships between all six subsystems. Although its shape has the biggest influence on others, the material should still be considered because it will have an impact on the environment. During the study of which form to employ, the shape of the voxel was determined. This will be set as a constant and will not be modified again. The form will now influence the interconnection of voxels, the geometric configuration of the robots, local mechanisms, and end effectors. The interconnections, on the other hand, will have a significant

impact on the end effector since the end effector must be able to (dis)connect the voxels, and this, along with the shape of the voxel, will have an effect on the cellular structure. It will have an impact on structural integrity and (dis)assembly in this case. Finally, the structure, linkages, and overall robot will affect how the system may be used in relation to its environment and how sustainable the overall system is.

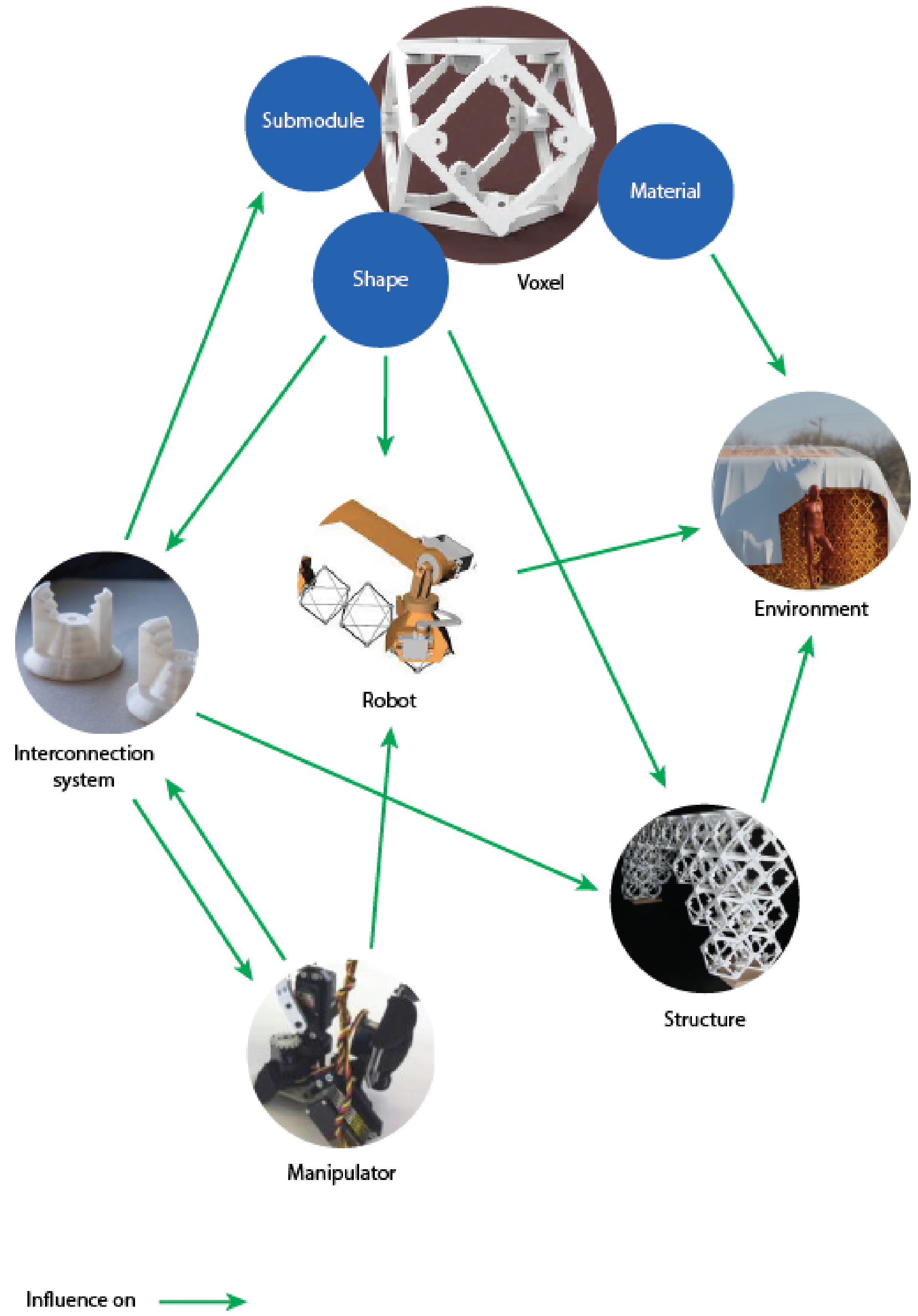


Figure 20. Influence of each subsytem on each other

2.4 Problem definition

"Design, develop and demonstrate a novel concept of a robot-material system, to facilitate a new and sustainable way of building up structures in situ, by allowing easy (dis)assembly and thus ease of repair and maintenance."

2.4.1 Program of Requirements

A list of requirements for the robot-material system has been established and differentiated by individual subsystem based on the research and findings. Table 4 contains a list of requirements, and Appendix C contains a more detailed version.

Table 4. Program of Requirements

List of requirements	Type	Specification
Voxel inter connection system		
Connection	Demand	The connection system should be integrated in the voxel
	Demand	The pin should be connected with only one movement
	Demand	The connection system should make the overall system less complicated
	Demand	The connection system should restrict sideways motion between two voxels
	Demand	The connection system should restrict vertical motion between two voxels
	Wish	The connection should should lock linear motion between two voxels
	Demand	The male pin holders should not interfere with the strut clearance of the voxel
	Demand	The connection should restrict bending movement
Lattice structure		
Assembly	Wish	A voxel should be able to be removed without removing surrounding voxels
	Demand	A voxel should be able to be placed without interfering with surrounding voxels
	Demand	The structure should be assembled autonomously
	Demand	The structure should be disassembled autonomously
Repair	Demand	Structure as a whole should be self supporting throughout the life and during assembly/disassembly/ repair/replacement process
	Demand	A failure of one voxel should not affect the performance of adjacent voxels
	Demand	It should be feasible to change one or a few voxels without affecting the integrity of the whole structure
General	Demand	The lattice structure should be reconfigurable
	Demand	The lattice structure should have societal relevance
	Demand	The lattice structure should be a potential improvement of the conventional solution
	Demand	The lattice structure should have (dis)assembly on location
Voxel		
Male	Demand	The voxel should have a weight of 420 grams
	Demand	The voxel should be 200x200x200mm
	Demand	The voxel should include 5 pin bridges
Female	Demand	The voxel should have a weight of 326 grams
	Demand	The voxel should be 200x200x200mm
General	Demand	The voxel should have two connection points on each side
	Demand	The voxel should be modular
	Demand	The voxel shape should make path planning more simple
	Demand	The voxel size should be able to change depending on the application
Robot		
Voxel placement	Demand	The robot should be able to place the voxel from each direction
	Demand	The robot should be able to place a voxel while standing horizontally
	Demand	The robot should be able to place a voxel while standing vertically
	Demand	The robot should be able to place a voxel that will be surrounded by 4 other voxels
Movements	Demand	The robot should be able to move horizontally
	Demand	The robot should be able to move vertically
	Demand	The robot should be able to move in one straight line without interfering with surrounding voxels
	Demand	The robot should be able to move on structure while holding a voxel
	Demand	The robot should be able to rotate to change direction
features	Demand	The robot should be able to walk around with a voxel with a weight of 420 grams
Feedback system	Demand	The robot should be able to know when to adjust its feet
	Demand	The robot should be able to know when a voxel is (dis)connected
	Demand	The robot should be able to know its place on the structure with reference to the launch pad
	Demand	The robot should be able to know when a voxel is placed
End-effector		
Accesibility	Demand	The manipulator should be able to acces the inside of the voxel
	Demand	The manipulator should be able to acces the connection system
Connection	Demand	The manipulator should be able to connect a voxel with only 10 movements
	Demand	The manipulator should be able to align two neighbouring voxels
Movement	Demand	The manipulator should be able to hold the voxel while the robot moves
	Demand	The manipulator should be able to rotate the voxel
	Demand	The manipulator should be able to remove the voxel horizontally
	Demand	The manipulator should be able to place the voxel horizontally
Electromagnet holder	Demand	The holder should be able to rotate 90 degree
	Demand	The electromagnets should be able to be activated seperately
	Demand	The electromagnets should have an attracting and repelling stand
	Demand	The electromagnets should repel to connect the voxel
	Demand	The electromagnets should atrract to disconnect the voxel
Environment		
Production	Demand	The structure should reduce production waste
	Demand	The structure should reduce the waste stream
	Demand	The structure should reduce disposal costs
Use case	Demand	The structure should be able to work as a shelter

03 Ideation

The ideation phase started with the findings from the research and analysis conducted on the different connection methods. It is also kept in mind to keep hierarchal modularity for cellular structures within the 2nd order hierachy level (Gawde, P. R., 2021).

In Table 5 the start case of the 2nd order hierarchy level is tabulated where Gawde left off. The term sub-module is used to refer to the 0th order hierarchical element. These submodules when assembled together in a predetermined repetitive pattern constitute a module. A module is defined as the 1st order hierarchical element and is the cellular unit cell in most cases. These modules are further assembled together to build the desired cellular structured geometry. This cellular structure is termed as the 2nd order hierarchical element. It can also be used further as a building block to construct yet another structure. However, increasing the hierarchical levels than the 2nd order might lead to a complex and time-consuming assembly line. Hence, it is limited to 2nd order hierarchy for modularity in cellular structures.

This case is used as a starting point to keep unity in the system when the connection system would be changed from bolts and nuts to a new one.

Table 5. Possible cases for hierarchical modularity in cellular structures (Gawde, P. R., 2021)

Hierarchy level	0th order submodule	1th order module	2nd order structure
Case 1	Struts and Nodes	Unit cell or specific voxel	Unit cell or specific voxel
Case 2	Face/Planar (2D) element	Unit cell or specific voxel	Unit cell or specific voxel
Case 3	Semi-3D element	Unit cell or specific voxel	Unit cell or specific voxel
Case 4	-	Unit cell (3D element)	Unit cell (3D element)

3.1 Connection system

Figure 21 shows how the present version of the robot-material system which is coupled through bolts and nuts, complicating path planning and voxel setup. The connection between the voxels impacts the overall system and should thus be examined first to establish a starting point for further system development.

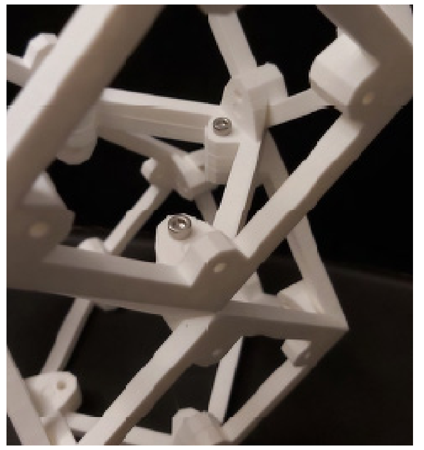


Figure 21. Use of bolt and nut to connect two voxels (Gawde, P. R., 2021)

The exploration of the three types of connections determined on in Section 2.2.1 kicked off the brainstorming process. The first mechanism to consider is a sliding mechanism, such as the dovetail in Section 3.1.1, followed by a pin system in Section 3.1.2.

3.1.1 Sliding mechanism

The dovetail mechanism was used to make voxel setup easier for the robot. Dovetail allows the robot to position the voxel vertically. It was rapidly discovered that this approach can link four voxels to each other, as shown in Figure 21, but more voxels on the same level and on top cannot be connected owing to a shortage of male components incorporated into the voxel.

More male parts are integrated on two faces and an extra one on top to be able to attach another level of voxels and to be able to attach a voxel next to the initial four voxels. This setup created the issue of a voxel being put vertically and horizontally at the same time. Attempting to resolve the issue resulted in the introduction of a multiplane dovetail mechanism, as seen in Figure 22. This arrangement comprises three male and three female sides. This fixed the problem because a voxel could now be placed horizontally and vertically, but it made path planning and voxel setup more complicated. Furthermore, this design would be tough to incorporate into the present voxel form.

In addition to the difficulties associated with this mechanism in voxel setup, the voxel would not be made of indentical submodules because two different sides would have to be manufactured. So when the structure is built, the male sides may protrude from the outside, which would reduce aesthetics and could be dangerous if something became stuck on it. For these reasons, this technique is abandoned in favor of a pin system in which the pins can move in and out of the voxels.

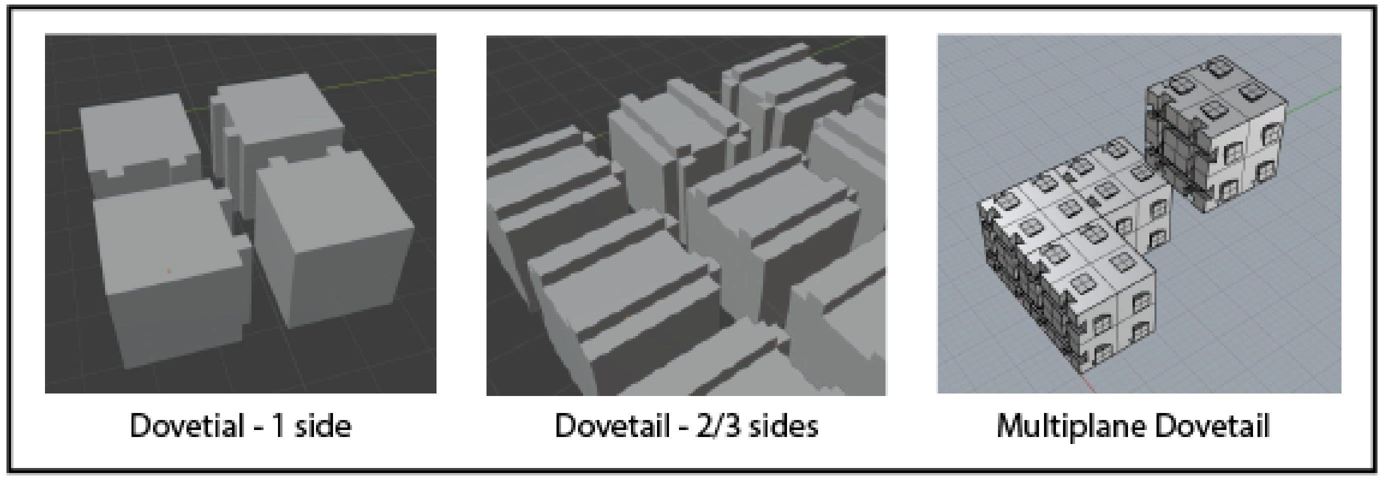


Figure 22. Dovetail idea iterations

3.1.2 Pin system

As seen in figure 22, idea 1, a basic and simple idea was to integrate two pins on two faces. The plan was scrapped since the voxel had to be positioned horizontally, which made it impossible for the robot to insert and detach them because they couldn't be moved vertically. Furthermore, when three voxels are placed, the fourth cannot be connected to the others.

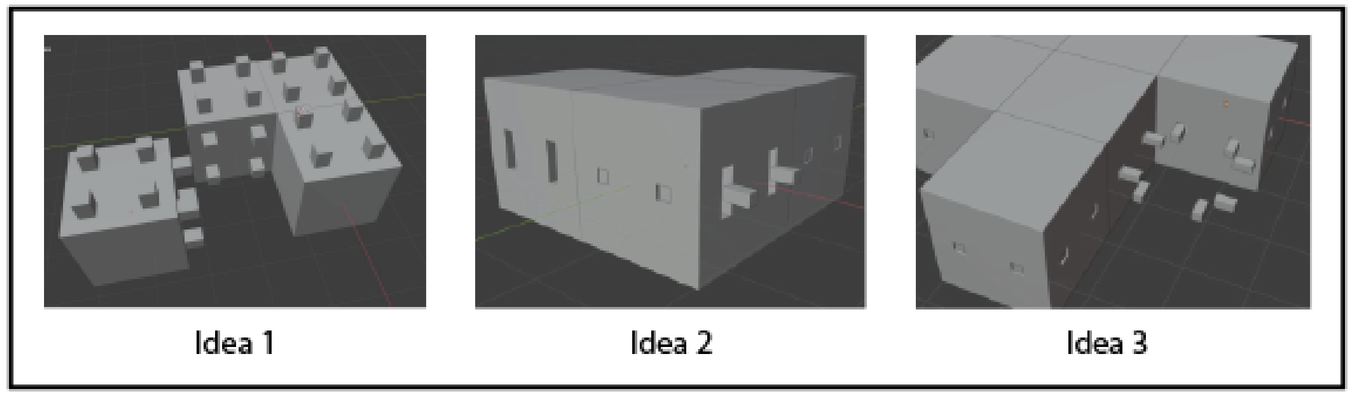


Figure 23. Pin concept iterations

Following the rejection of Idea 1, another possibility was to have the pins translate inbetween the voxels. The key benefits are that they'd be translated in the correct direction and that the voxel has flat faces. When a connection is made, the voxel will always have a male side that includes the pin and a female side that accepts the pin. The pin is moved without the application of any external force. Each side of the pin includes two magents. Both the female and male halves include a magnet, although the magnet within the female component is stronger.

As soon as the voxel is aligned, the pin will shift towards the female side. Despite the fact that the link is functional, the concept is abandoned. To detach the voxel, the female side would require a slid so that the pin could travel with the voxel and return to the male half when separated from

the female magnet. When the robot moves over the structure, this slid causes the voxel to move down since it produces a downward force, which might cause the voxels to detach.

The third concept is similar to the second, except that an external force will be used to move the pins. The slid will be removed, allowing the robot to navigate around the structure without separating the voxels. Because each voxel has a male and a female submodule, the voxels are not identical, hence the goal was to make the submodules androgyneous, as seen in Figure 24. Because the voxel now comprises submodules with male and female components, the manufacturing quantity is reduced to only one submodule, resulting in a identical voxels.

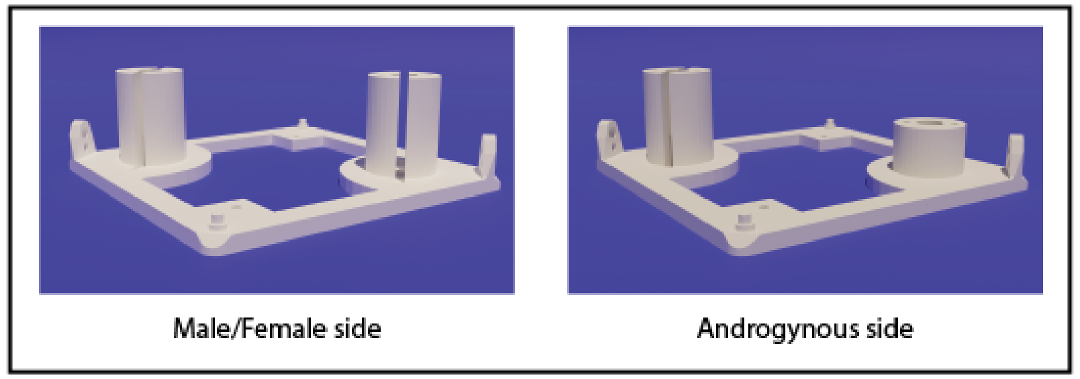


Figure 24. Pin system integration in submodule

3.2 Holding pins in place

3.2.1 Magnets

Because the pin already has two magnets, magnets might be employed to keep the pins in place. Inserting magnets into the male portion of the submodule will keep the pin in place and aid in translation when necessary. Figure 25 depicts the system's configuration.

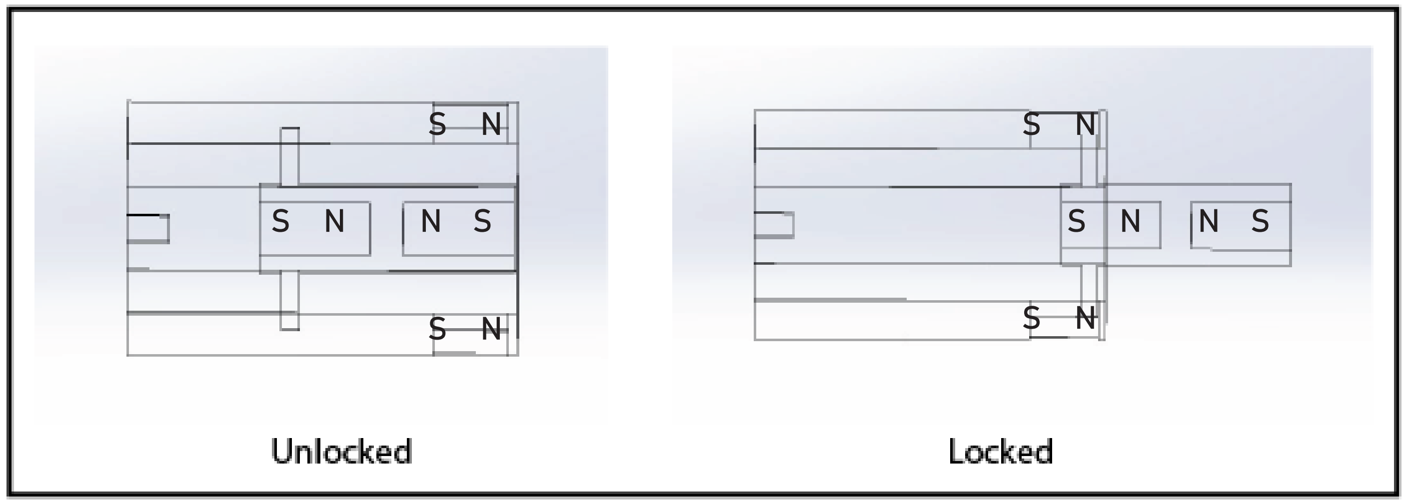


Figure 25. Holding pin in place via magnets

The magnets within the pin are placed with opposite polarity towards each other. The magnets in the male component must be the same polarity as the magnets in the pin's front part. When the voxels are not connected, this design may retain the pin on the male component, help it move towards the female half if a force is applied, and keep the voxels locked.

3.2.2 Compliant mechanism

Bitstable compliant systems have the advantage of being constructed with two stable locations that can retain the pin in an unlocked and locked condition. The original concept was to incorporate a compliant system within the male components. Figure 26 depicts the design that sparked the concept.

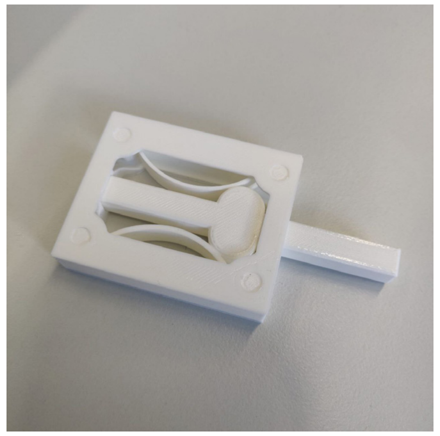


Figure 26. Compliant system inspiration

The pin has a bumper in this case, which will interact with the spring inside the system. To go to the opposite stable position, the pin would have to overcome this unstable point. Iterating on this system yielded the following concept, depicted in Figure 27.

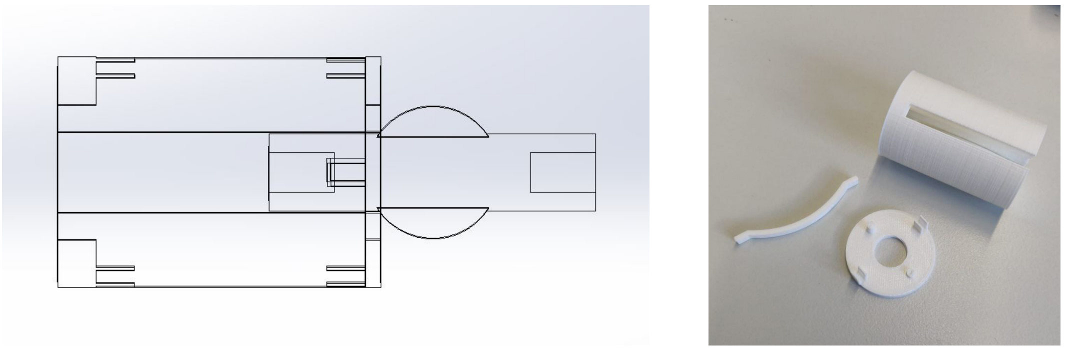


Figure 27. Concept 1 for compliant system

The part has two springs and holds the pin, allowing it to move between stable positions. Because this system uses several components, the assembly of a voxel becomes more difficult and expensive. Another significant feature of compliant systems is that they are frequently constructed from a single element, as shown in Figure 28. In its initial stable position, the component is constructed as a single piece. By moving the pin, it will travel to an unstable position and be pushed by the springs to the opposite stable point.

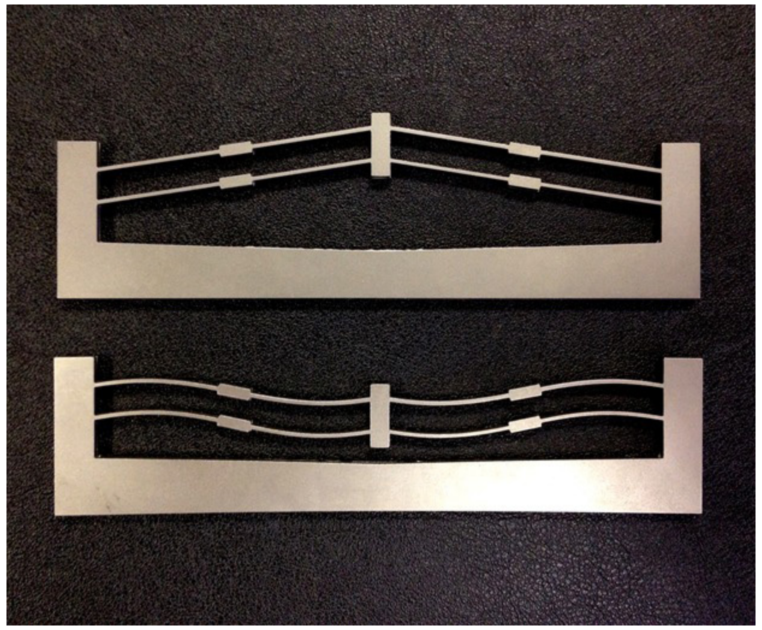


Figure 28. Compliant system manufactered from one part
(Homer, E., et all, 2014)

3.3 End effector

The end effector of the robot should hold an end effector to operate the connections between voxels. An end effector is a peripheral device that attaches to a robot's wrist, allowing the robot to interact with its task. Most end effectors are mechanical or electromechanical and serve as grippers, process tools, or sensors. They range from simple two-fingered grippers for pick-and-place tasks to complex sensor systems for robotic inspection (Automate, 2020).

Currently no end effector has been designed based on the connection system that will be used during this project. Due to the complicated environment the robot shall operate in, it was considered to decide between a rigid or soft end effector.

Table 6. Benfit comparison between soft and rigid robotics (Fu, Chiyu et al., 2022)

Soft Robotics	Rigid Robotics
Compliant	Efficient
Safe interaction	High durability
Flexible	Precise control
Lightweight	Risky interaction
Environmental friendly	Expensive
	Bulky

Based on the cellular structure a thorough comparison could be conducted, as seen in Table 6. Since the robots would be working in risky environments and interact with the structure, using soft robotics would be a good choice. It is flexible which makes it easy to reach tight spots and create a safe interaction with the structure. Soft robotics is lightweight which is beneficial for transportation reducing the cost of the robot-material system. On the otherhand soft robotics have unpredictable behaviours and are not precise.

Since these are important factors and looking at the timespan of this project it is decided on to work with rigid robotics for the end effector. This makes the goal achievable and create a more reliable end effector. The main purpose of the end effector is to push in the pin and pull the pin out. Complexity of the robot can be reduced by lowering the degree of freedom of the end effector and is therefore also considered while designing.

3.3.1 Rigid end effector

Electromagnets are used inside the end effector to translate the pins in and out the voxels. They are made of a metal core with a copper wire winded around. The mangnetic field force depends on the current fed throught the coil, the amount of windings and the lenght of the coil used, as seen in Figure 29.

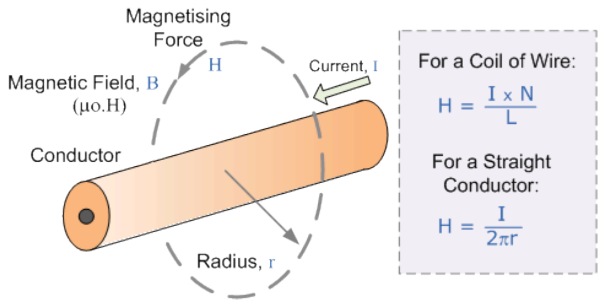


Figure 29. Formula to calculate to magnetic force in an electromagnet (Storr, W., 2018)

When using electromagnets it should be taken into account that the surface area of the electromagnet has to be smaller or equal compared to the holding surface. As well as that off-the-shelf electromagnets are usually electropermanent magnets which work as electromagnets but also include permanent magnets to create a stronger attracting force. Resulting in a lower repulsive force therefore only electromagnetic coils will be used in this design (Nafsa, 2015).

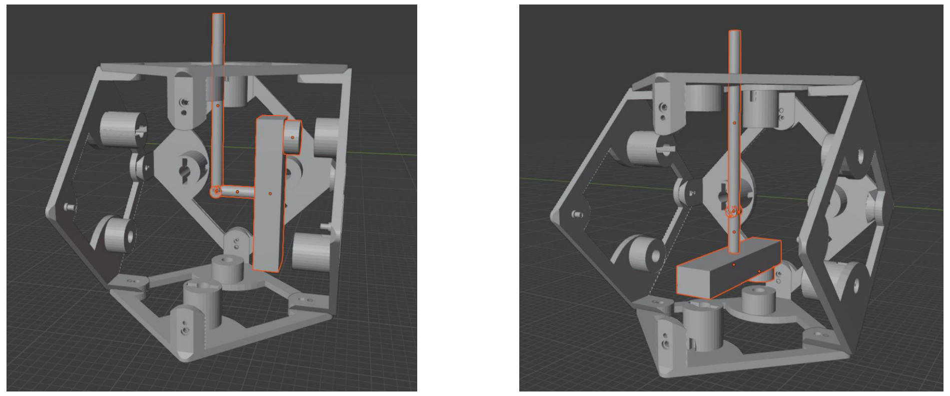


Figure 30. Idea 1 for the end effector (Left: Locking right side, Right: Locking bottom side)

The fist idea followed from the pin concept and submodule decided on in Section 4.1 and Section 4.2 respectively. Figure 30 displays the end effector that would be holding two electromagnets. One electromagnet would stick out to reduce the distance between the end effector and the female pin holders. This idea needs four actuators for the end effector to reach all pins and 14 movements to be able to (un)lock all five sides.

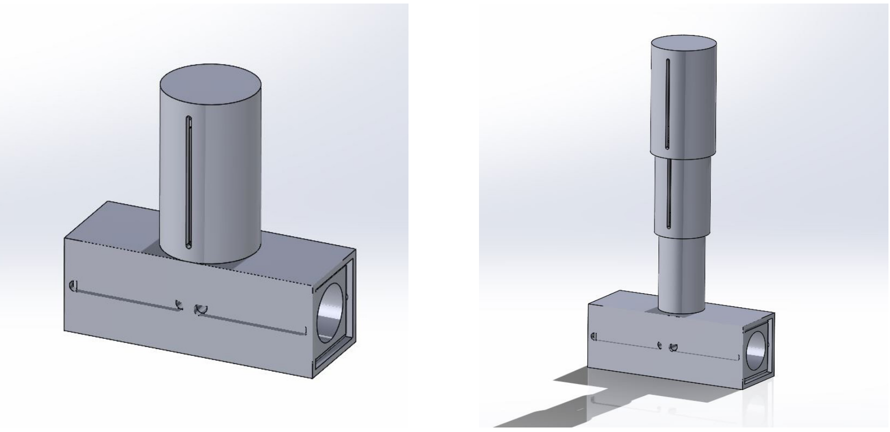


Figure 31. Idea 2 for the end effector (Left: initial configuration, Right: Extended to reach pins)

The second idea is designed with the idea of reducing the degree of freedoms in the end effector. For this idea to succeed the submodule had to be redesigned as can be read in Section 4.3. Creating a male and female submodule creating equal distances within the voxel which reduces complexity in the end effector.
The end effector has three actuators to position it in the right locations. Figure 31 depicts the translating motion to enter the voxel and to position the end effector at the rigth location. The end effector is also able to rotate around its main axis and the one perpendicular on the main axis. To (un)lock the pins four electromagnets are used. Two who are capable of translating outwards as depicted in Figure 32 and two are integrated in the bottom. This idea has a total of four actuators and needs 10 movements to (un)lock all five sides.

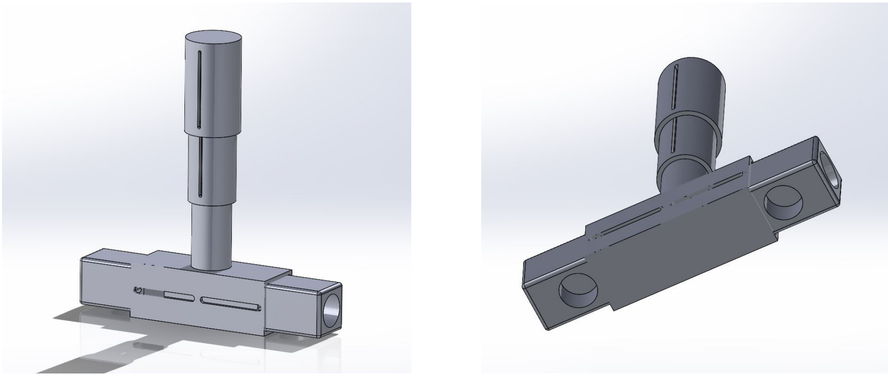


Figure 32. Idea 2 for the end effector with extended electromagnets
(Left: Side electromagnets, Right: Bottom electromagnets)

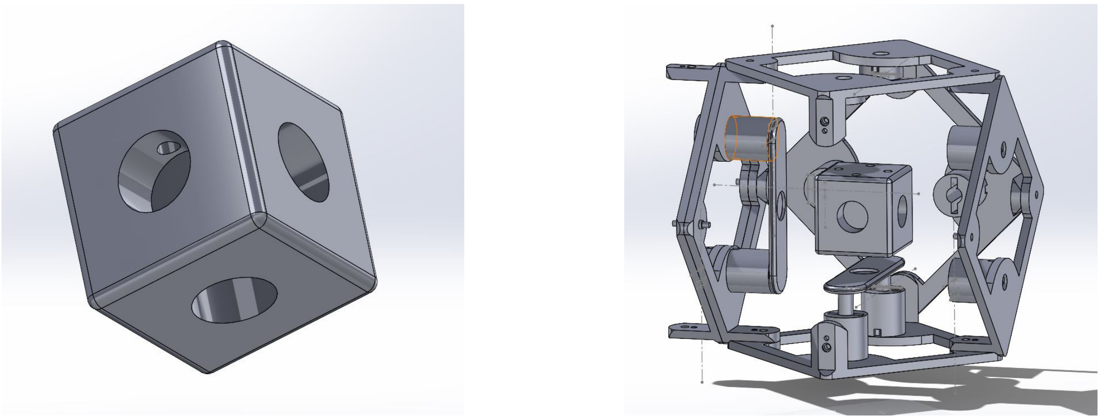


Figure 33. Idea 3 for the end effector
(Left: Electromagnet holder, Right: Holder inside a male voxel)

The last idea is desigend to reduce the DOF to only one. To achieve this the male and female submodules are used togheter with the latest iteration on the pin system. By bridging the pins and elongating them as can be seen in Section 4.3. The end effector does not need electromagnets to translate outwards as well as it only has to move to the middle of a voxel. The end effector will hold five electromagnets, for each side one, which reduces the end effector DOF to only one downward movement and one actuator. The electromagnets can be activated seperatly so that the robot can still decide which sides to (un)lock.

Table 7: Comparison between the three end effector concepts

	Concept 1	Concept 2	Concept 3
Movements	14	10	1
Actuators	4	4	1
Electromagnets	2	4	5

Considering that the robot should be as simple as possbile the DOF should be reduced to a minimum. It can be viewed from Table 7 that an increase in actuators also creates an increase in movements. Eventough it might reduce the amount of electromagnets and therefore the weight as well, since the electromagnets would be the heaviest component. Therefore idea 3 is decided to work further with and develop since it makes the system the least complex.

04 Conceptualization

The concept of a translating pin system to construct a structure built of cuboctahedral modules was expanded upon and iterated for improvements in order to meet the criteria and needs outlined in the program of requirements (Section 2.4.1). The concept required significant changes in the following areas:

Interconnection system:

1. The connection mechanism should be built into the voxel.
2. The connection mechanism should limit vertical and horizontal movement between two voxels.
3. A voxel should be able to be removed without affecting neighboring voxels.
4. The male pin holders should not impede with the voxel's strut clearance.

End effector:

1. The end effector should be able to acces the connection system
2. The electromagnets should be able to be activated seperately

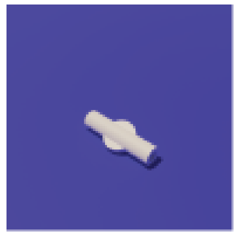
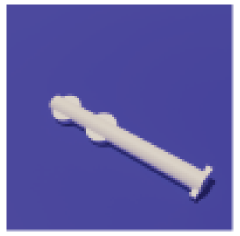
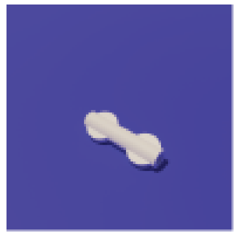
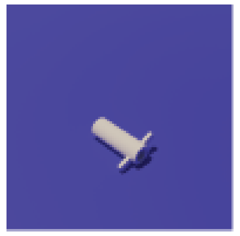
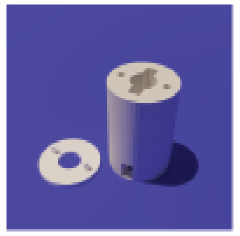
All iterations were designed in SolidWorks software and printed on a fused deposition modeling 3D printer - Ultimaker 2+ - with a 15% infill density for Polylactic acid (PLA) material.

4.1 Pin & Pin holder variations

The pin and pin holder iterations are based on the ease of (dis)assembly to restrict movement in any direction and the ease of moving the pin inside the holder. Concerns have been raised about how to relocate the pin and maintain it in place when the voxel is in a (un)locked state. Before the voxels are joined, not a single pin can protrude since this would prevent a voxel from being inserted between other voxels. Vertical and horizontal movement restrictions are critical for the robot's path planning and voxel setup. Finally, when the pin system is incorporated into the submodules, it should not interfere with the strut clearance, allowing the end effector to move freely within a voxel.

Iterations on a compliant mechanism and a kinematic coupling system ensued. In both conditions, the compliant system had difficulty moving the pin and maintaining it in position. The usage of PLA as a material might be one cause for this. It features a rough surface, which causes friction between the pin and the spring within the holder. Furthermore, PLA is rather rigid, and a more flexible material would be desired for a compliant system. However, challenges with the kinematic system to correctly keep the pin in position and magnet configuration were noticed. In terms of the requirements, numerous iterations were carried out in order to arrive at the best solution. Table 8, Figure 34 and 35 show the iterations and a system overview, respectively.

Table 8. Iterations on the pin and pin holder

Iterations	Pin / Pin Holder	
Iteration 4.1.1		Compliant system
Iteration 4.1.2		Compliant system
Iteration 4.1.3		Compliant system
Iteration 4.1.4		Kinematic coupling
Iteration 4.2.1		Compliant system
Iteration 4.2.2		Kinematic coupling

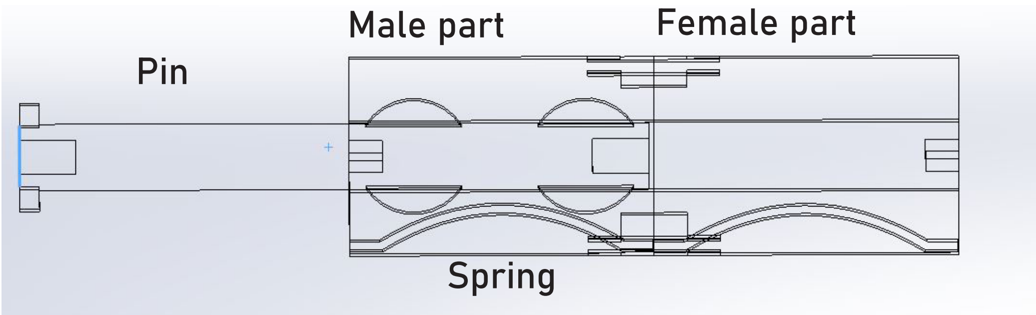


Figure 34. System setup for the compliant system

The following is how the compliant system works, depicted in Figure 34. When the pin is latched into the male component, it will be in the initial stable position. When the pin is pushed, the back bumper must go over the first spring and the front bumper must go over the second spring. This is the point at which the posture becomes unstable. The pin is subsequently moved forward to the second stable point, connecting the two voxels and limiting movement in both horizontal and vertical direction.

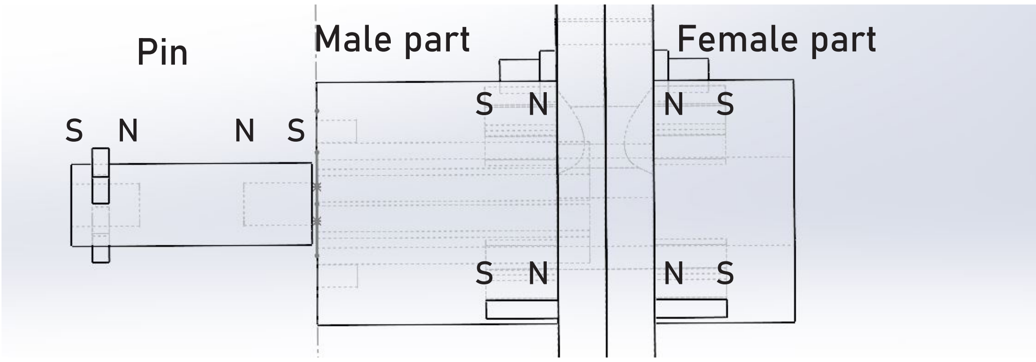


Figure 35. System setup for the kinematic coupling system

The kinematic coupling system, presented in Figure 35, functions as follows. When the pin is secured into the male portion, the magnets inside will attract and hold the magnet within the pin in place. The magnets within the male and female portions will assist when the pin is triggered to travel forward to link two voxels. The magnets in the male portion will repel the pin when their north poles cross. And the pin is made in such a manner that the front magnet may cross the magnets within the female section, connecting the south poles to the north pole of the magnet inside the pin. The same is true for the magnets in the pin's back and the ones in the male portion.

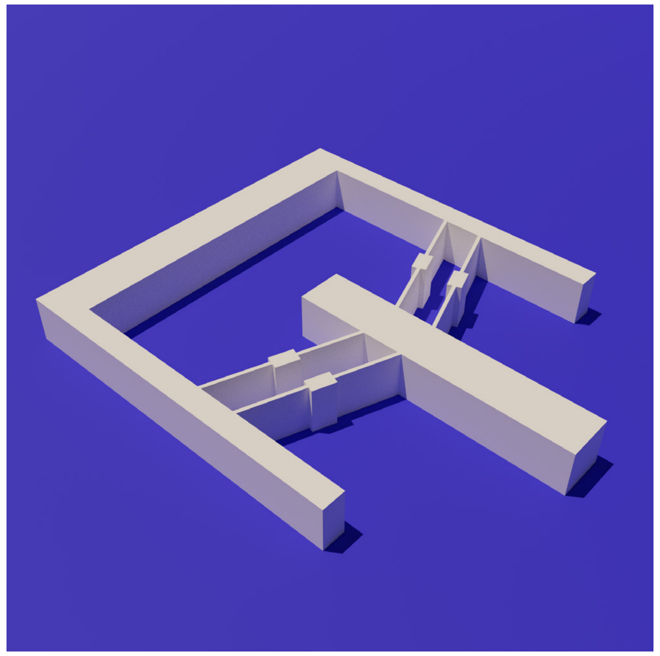


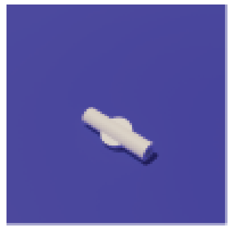
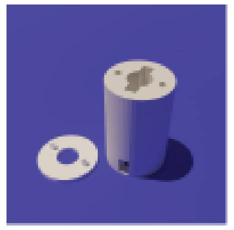
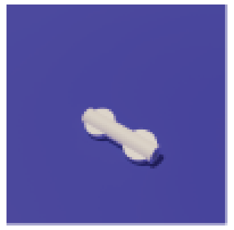
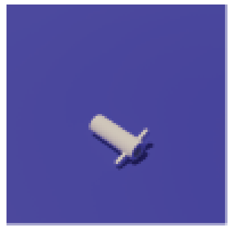
Figure 36. Compliant system printed in one part

The benefit of a compliant system is that it is built from one part, seen in Figure 36, however the other compliant version requires a number of pieces, which dilutes the purpose of a compliant system. This concept was produced and tested, but it was immediately abandoned. It would be very difficult to include it into the submodules. The submodules are 3D printed, and incorporating this design would need extra support, which would increase post-production, manufacturing time, and expense. Table 9 depicts the different pin-holder arrangement variations.

The kinematic coupling concept proved to be the most reliable option. It outperformed the complying system in terms of functionality. Using magnets inside the pin and the holder reduces friction, requiring less force for the end effector to actuate the pin. This allows the pin to effortlessly transition from the unlocked to the locked state. In addition, the magnets assisted to maintain the pin in place so that no disturbances could displace it.

As a result, the kinematic coupling system was chosen as the current concept for the pin-holder design. This notion will be implemented into the submodule in Section 4.2, and more iterations will be undertaken.

Table 9. Description and discussion on the pin and pin holder

Pin	Description	Discussion	Pin Holder	Description	Discussion
 Iteration 4.1.1	- Pin with one bumper to overcome the spring in the pin holder (4.2.1) - Pin holds two magnets	- Pin is able to overcome spring and jump to the other stable position - Pin still can move out of the pin holder - Pin cannot keep two voxels together	 Iteration 4.2.1	- Pin holder with two springs and closing lid	- The pin holder has too many parts resulting in more production time and cost - The spring material is too stiff for the pins to move easily and too rough creating too much friction
 Iteration 4.1.2	- Pin length is increased - Pin has an extra bumper	- The extra bumper helps the pin to be kept in place when inside the pin holder (4.2.1) - Increase in length was for convience but makes it more difficult for the manipulator to move inside the voxel	 Iteration 4.2.2	- Pin holder with two magnets and closing lid	- The pin holder is able to keep the pin in place when in (un)locked state - Easier to manufacture with 3D printing
 Iteration 4.1.3	- Pin length is decreased - Bumper amount is kept the same	- The pin lenght is suitable for the manipulator to move around			
 Iteration 4.1.4	- Pin has one bumper to be stopped in pin holder (4.2.2) - Pin hold two magnets	- Pin is kept in place due to the mag nets used in the pin and in the pin holder (4.2.2) - Magnets help to attract and repel the pin by the manipulator			

4.2 Submodule

The current pin-holder configuration, selected in Section 3.2, has been integrated into the submodule decided on in Section 3.1.2. The same criteria were utilized to iterate on this notion in order to address the remaining issues. The first notion tested was the incorporation of electromagnets into the submodules, as seen in Figure 37.

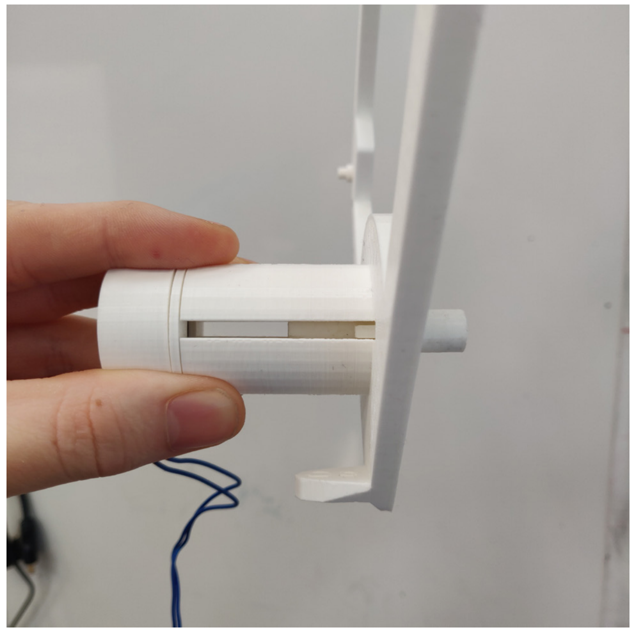


Figure 37. Integration of the electromagnet in the submodule

The system would function as follows: both the male and female components would have an electromagnet connected at the end, and the pin would have a weaker magnet pointing to the male side and a stronger magnet pointing to the female side. The notion is that when the robot end effector holds the voxel, it generates a current. The pins will retract, and the current will decrease to zero as soon as the voxel is placed.
On the other side, the electromagnet will function as a ferrous metal, and the pin will travel in the female side, connecting both the male and female sides. Furthermore, if the voxel is not encircled on all sides, the pins will remain in place for the same reason they would move. The system is depicted in Figure 38. One of the significant problems of this approach is that 12 electromagnets would be incorporated in one voxel, causing strut clearance to be compromised. This idea was scrapped due of the added cost and weight of the voxels.

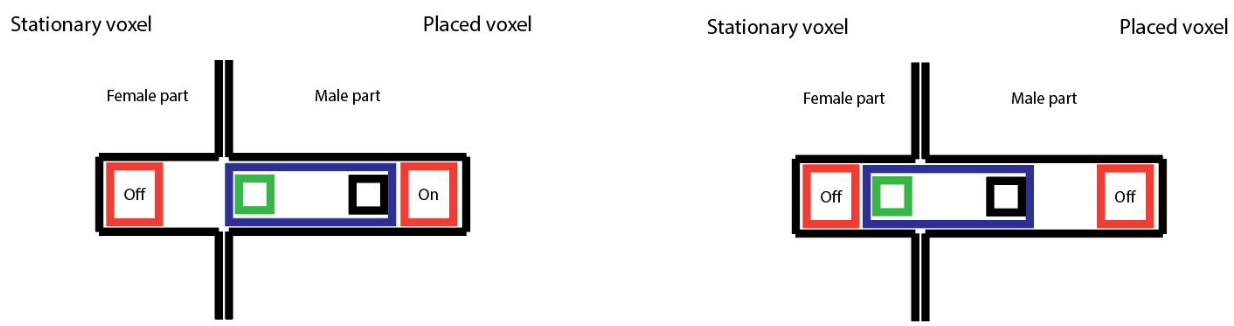


Figure 38. System setup of the electromagnet in the submodule

If electromagnets were employed to move the pins between voxels, it was determined that they would be integrated into the robot's end effector. This brings the total number of electromagnets down to a maximum of five. The next step was to put the present submodule design to the test and refine it through iterations. This resulted in the present set of six iterations, which are described and discussed in Table 10.

The second last iteration proved to be the most dependable. In terms of functionality and application to the requirements, it outperformed the preceding versions. The present design, depicted in Figure 39, is incorporated into the voxel submodule and does not interfere with strut clearance, allowing a stiff or soft mechanism to be used as the robot's end effector. The submodules link easily, which performs alignment when placed thanks to the magnets. Furthermore, the pins do not require a lot of force to move and will restrict movement in all three DOF. Finally, nothing protrudes, making assembly and disassembly simple, resulting in a modular construction. As a consequence, as indicated in the picture, iteration 4.1.6 has been to most promosing modular idea for the submodule design. The next stage is to create an end effector capable of linking and disconnecting numerous voxels.

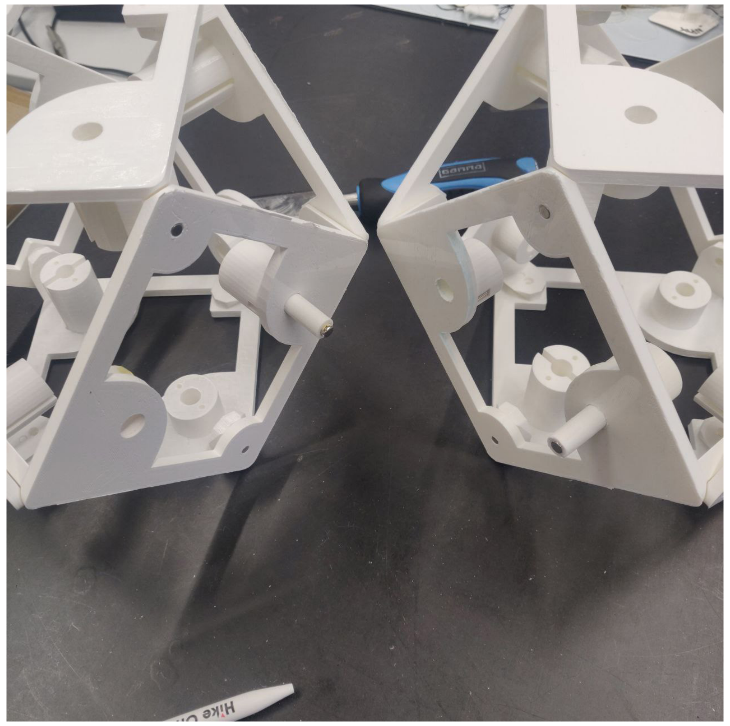
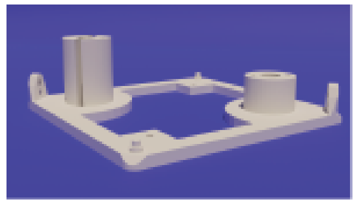
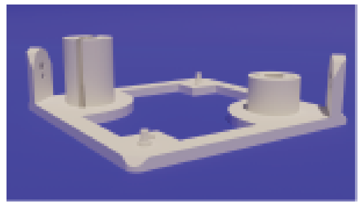
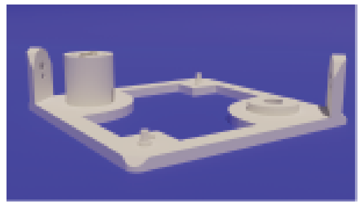
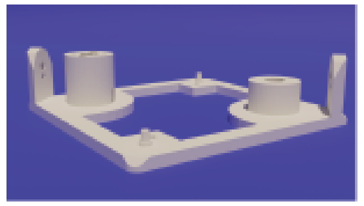
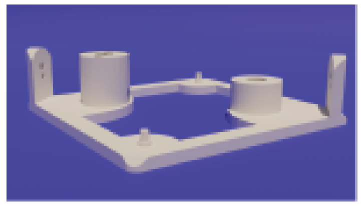
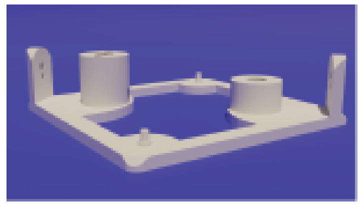
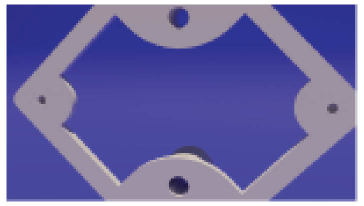


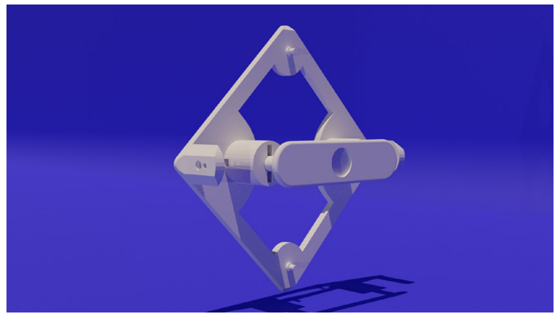
Figure 39. Current voxel and interconnection system

Table 10. Description and discussion on the iterations of the submodule

Iterations	Submodule	Description	Discussion
Iteration 4.1.1	 	- Male/Female pin holders were tested - Male holder has a slid to translate pin in one DOF - Peg-Dowel are kept the same as in Granav's submodule design	- The pins restrict two voxels from rotating, but they are not locked so they can move freely - This configuration cannot connect two voxels - Peg-Dowel system cannot trasfer a lot of load due to the small area, creating weak links between the submodules
Iteration 4.1.2	 	- Male/Female pin holder were kept the same - Dowels are moved inwards and increased in height - Pegs are increased in height and thickness	- Peg-Dowel system is stronger and easier to connect two submodules
Iteration 4.1.3	 	- Male pin holder is decreased in height and two small gaps are integrated to place magnets - Female pin holder is decreased in height - Pin is able to translate but is stopped by the female holder instead of the male holder	- Magnets inside the male pin holder are able to hold the pin in place in the (un)locked state - Pins push against the other voxel when in locked state, creating a gap inbetween the voxels - Voxels are still able to move horizontally from each other, so the voxel can disconnect.
Iteration 4.1.4	 	- Male pin holder is kept the same - Female pin holder is increased in height and two small gaps are integrated to place magnets - Pin is able to translate but is stopped inside the male holder	- The magnets inside the female part help the pin stay in place and keep the voxels connected
Iteration 4.1.5	 	- Male and female pin holder are moved closer too each other - Fillet is added on the intraconnection area	- The rigid manipulator has the right lenght and is able to move inside the voxel and move around
Iteration 4.1.6	 	- Two small holes are added on the bottom to insert two small magnets to align the voxels	- The magnets will cause the voxels to align by themselfs reducing complexity of the manipulator - The magnets help to keep the voxels together

4.3 End effector

Before performing the test of connecting the pins to start of the end effector design explained in Section 4.3. One more iteration was made on the voxels and their submodules. The modular design is very usefull for limiting the amount of parts and the prodcution time, still it was discovered that this would create a more complex end effector. The idea is to have an end effector that can connect a voxel with the least amount of movements.
Following this requirement it has been decided on to work with two types of voxels, namely male and female. The male voxel will consist out of 5 male submodules and 1 female submodule, presentend in Figure 40. Whereas the female voxel will consist out of 1 male and 5 female submodules. The pin system is theirfore also simplified by creating a pin bridge, depicted in Figure 41. The iteration would make it feasible for the end effector to connect a voxel with only two movements. Therefore it was decided to have a bit more parts to make the voxels which will simplify the overall robot-material system.



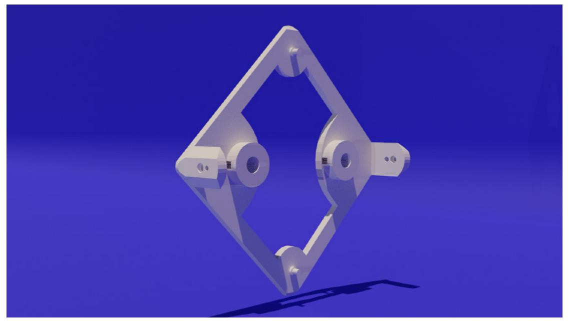


Figure 40. Left: Male submodule, Right: Female submodule

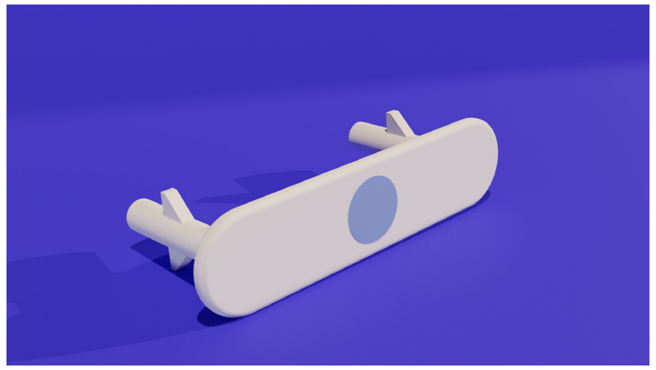


Figure 41. Pin brdige configuration

To begin conceptualizing the end effector, all components, which can be located in Appendix D, in the bill of material, had to be gathered. A preliminary test was performed using a self-made electromagnet and an H-bridge to reverse the current, achieving repelling and attracting electromagnet cycles. The test setup is depicted in Figure 42.

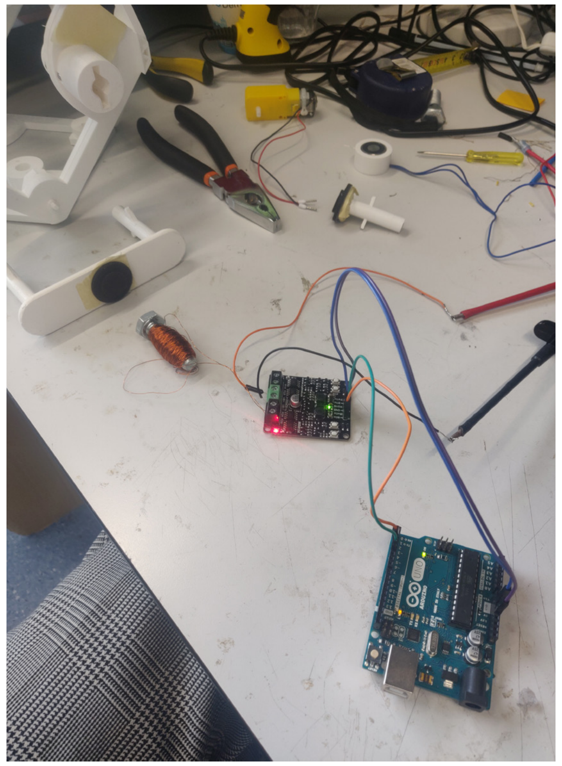


Figure 42. Preliminary test setup

A generator supplied 15 V and 1 Amp to the system. The H-bridge was programmed using the pseudo code shown below and the full code can be found in Appendix G. This code constantly reverses the current to see if the electromagnet is powerful enough to attract and repel the pin.

```
void loop() {
  Set pin 1 LOW
  Set pin 2 HIGH
  delay(4000);

  Set pin 1 LOW
  Set pin 2 LOW
  delay(2500);

  Set pin 1 HIGH
  Set pin 2 LOW
  delay(4000);

  Set pin 1 LOW
  Set pin 2 LOW
  delay(2500);
}
```

Because it was constructed with a bolt, the electromagnet had two distinct surface regions. As a result, both sides were examined to determine how large the electromagnet's surface area needed to be. The test is also used to determine the distance of the air gap between the electromagnet and the magnet, so that the electromagnet can repel the pin.

It was discovered during the test that an air gap of 6 mm is adequate for the electromagnet to repel the magnet when they are close to each other. To keep the electromagnet at a safe distance, felt pads that are not conductive were employed, as shown in Figure 43.

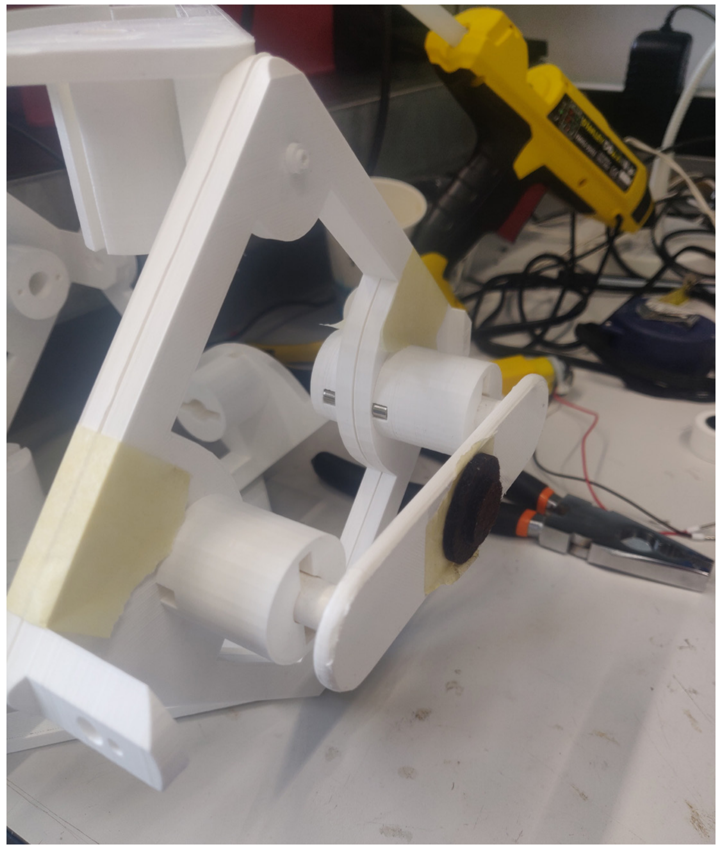


Figure 43. Bridge pin inserted in voxel submodule

When the smaller and larger areas of the electromagnet were studied, it was discovered that attracting the pin functioned as expected, but when both were required to repel, the smaller area could shoot the pin away, whilst the pin simply fell down when the larger area was used to repel the pin. Implying that the electromagnet should be smaller than the magnet. Another cause could be that the electromagnet is not uniform causing the magnetic field also to be uniform making one side stronger than the other. This is not verified due to it not being relevant for further design of the end effector

The distance between the electromagnet and the pin determines whether the electromagnet can attract or repel the pin. This distance is determined by doing a brief test in which the electromagnet is activated at various distances. Figure 44 depicts the test setup.

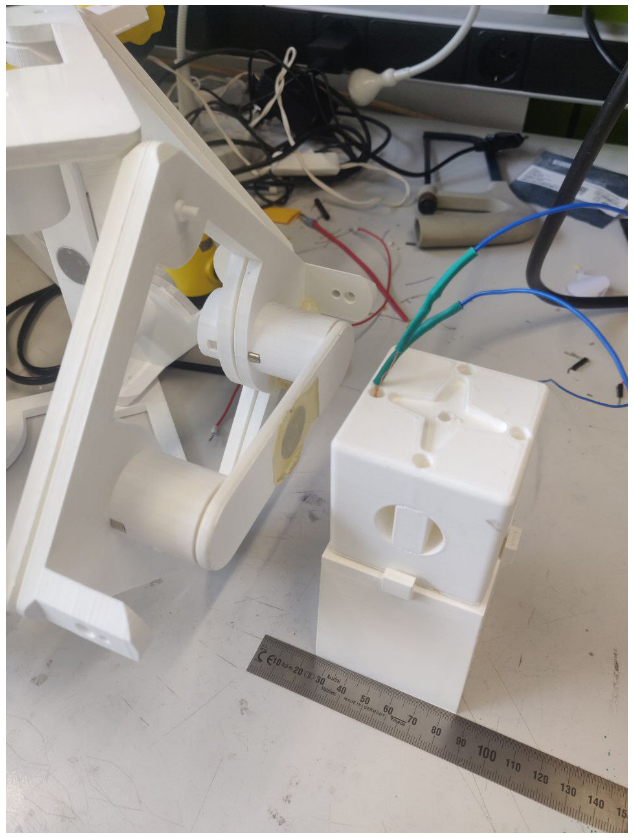


Figure 44. Distance test setup

A new electromagnet with a smaller core and 650 spins is employed for this test. This electromagnet has a larger magnetic force than the self-made electromagnet since it has a current of 2.2 amps at a voltage of 12 volts. As a result, the maximum distance recorded where attracting can occur is 1.8 cm.

After the tests, other requirements are decided on that the end effector should apply to. The following requirements are added to the already existing list:

End effector:

1. The end effector should be able to rotate 90 degrees inside the voxel.

2. The end effector should be able to vertically move down.

3. The end effector should be able to reverse the current towards the electromagnets.

4. The distance between the electromagnet and the pin should be 1.8 centimeters.

5. The electromagnet should receive a current of 2.2 amps at 12 volts.

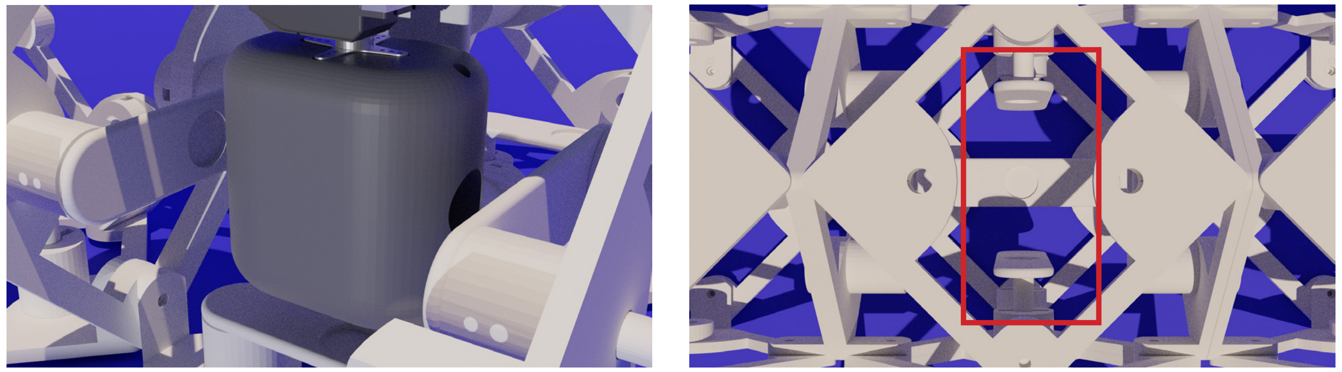


Figure 45. Left: End effector inside a male voxel,
Right: Top view male voxel

Figure 45 shows an electromagnet holder that can align with three voxel submodules at a distance of 1.8 cm. Because of the geometry of the submodule, it was discovered that using five electromagnets was not possible. The hole in the submodule has a rectangular shape, as shown in the picture, and it is only possible to obtain a spacing of 1.8 cm between the two opposite sides and the one on the bottom.

Assembling the end effector revealed that it is not accurate enough due to misalignments and material flexibility, as shown in Figure 46. The fundamental issue is that PLA is too flexible for the electromagnet holder's weight. In addition, the gear rack is very flexible. The gear rack's flexibility is evaluated by aligning the electromagnet holder with the Pin system and activating the electromagnet. In this test, the holder is pulled rearward when repelling the pin, resulting in an occilation, which causes the holder to move back towards the pin and attach. The plate rigidity is improved by placing a 9mm MDF plate beneath the PLA platform.

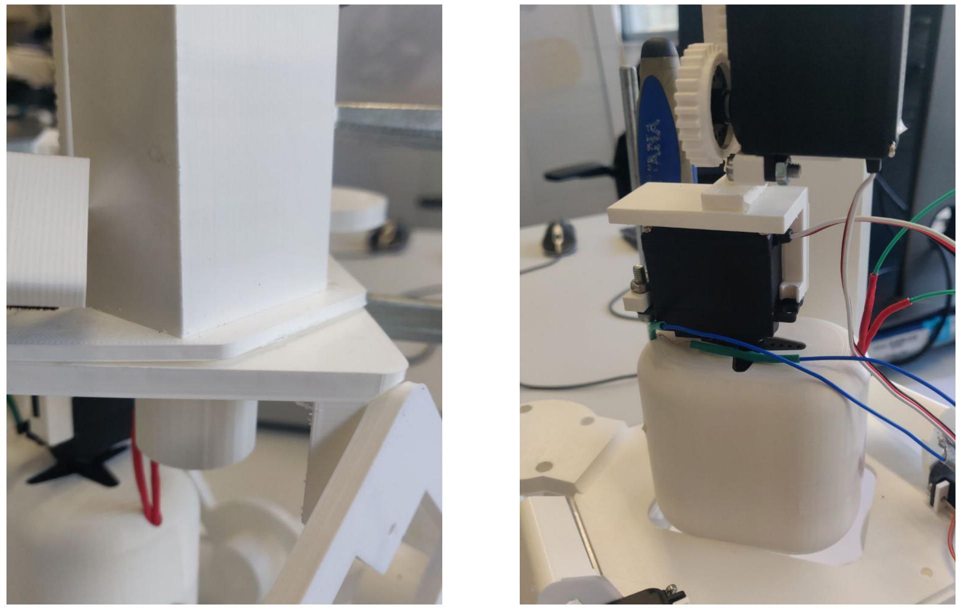


Figure 46. Left: Bending in end effector plate,
Right: Misalignment of the holder

By expanding the width of the gear rack and adding a rib on the back, the moment of inertia is enhanced, resulting in a stiffer design. Figure 47 show both solutions.

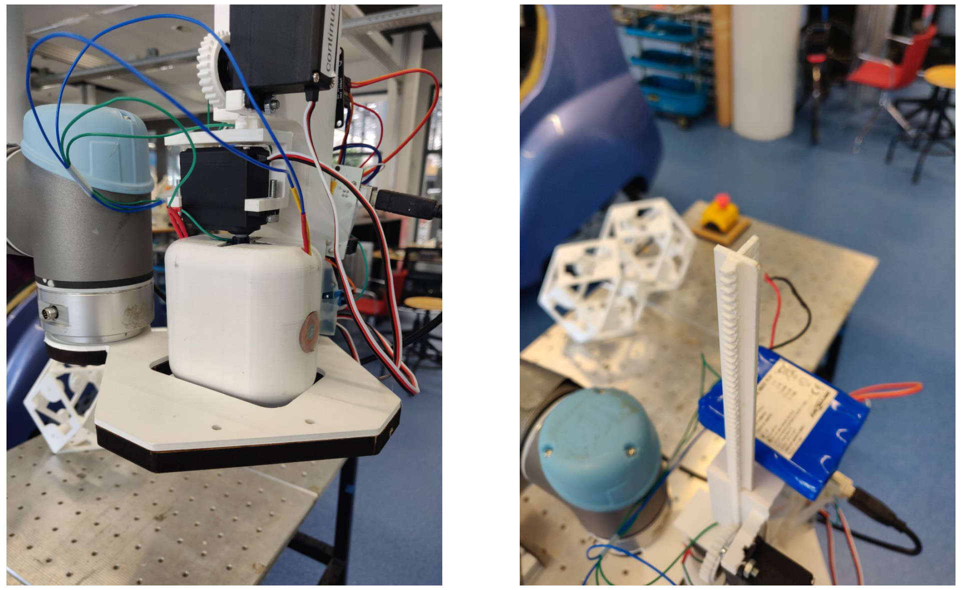


Figure 47. Left: FDM plate added to the plate,
Right: Rib added to the gear rack

05 Concept Evaluation

It was critical to evaluate the modular cellular structure on the ease of connection between many voxels after proposing the new connection mechanism in cellular structures. To keep the cellular structures' original utility, the voxels must be able to align properly and be connected in a floating fashion. The goal is to be able to attach voxels to bridge a gap without them falling to the ground, since the proposal idea is to build a bridge or dome roof with no additional support while connecting the voxels.

5.1 Specimens

The specimens used during the test are listed below in Table 11 and shown in Figure 48

Table 11. Specimens used during the evaluation test

Specimen	Description	Specification	Size	Weights
1	Male voxel	5 male submodules, 1 female submodule	200mm^3	420 grams
2	Female voxel	1 male submodule, 5 female submodules	200mm^3	324 grams

Both specimens are built from interconnected submodules designed by Gawde (Gawde P. R., 2021) and 3D printed on an Ultimaker 2+ with the specs specified in Table 12. All submodules have two magnets integrated at the bottom to align voxels while they are placed close to other voxels. A pin is intagrated in the male submodules to connect male voxels to female voxels via the end effector.

Table 12. Specimen specifications

Print parameter	Configuration
Material	PLA
Temprature(°C)	200
Speed (mm/s)	50
Infill (%)	15
Layer height (mm)	0.15
Wall line count	3
Wall thickness (mm)	1.2

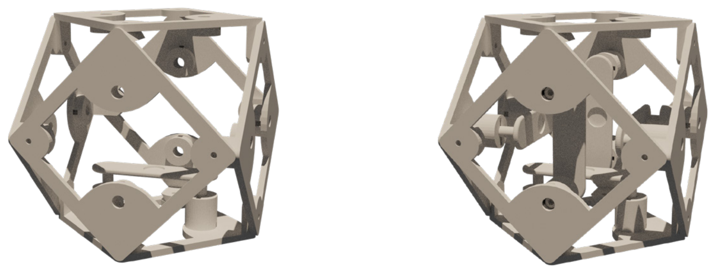


Figure 48. Left: Female voxel, Right: Male voxel

5.2 Test setup

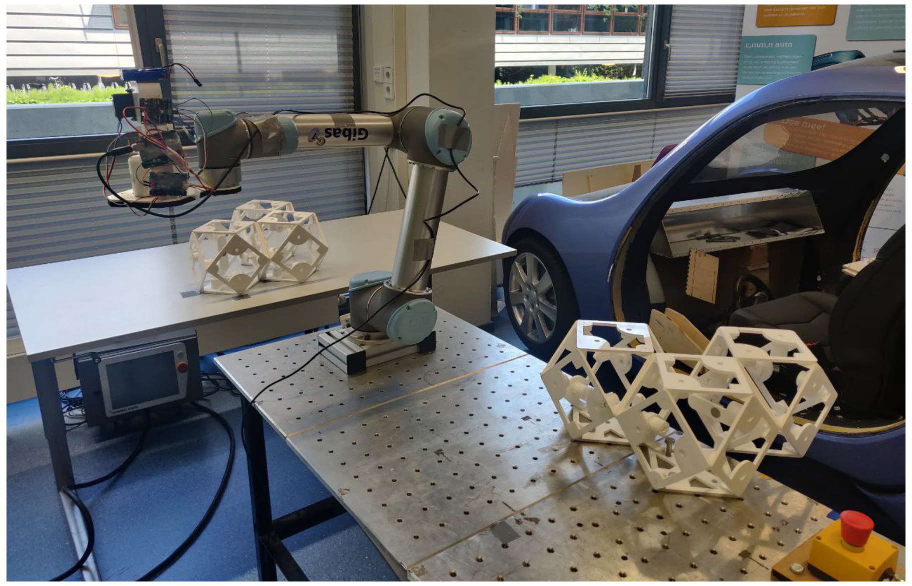


Figure 49. Test setup for evaluation the concept

When using autonomous voxel assembly for bridges or roofs, it is critical to test the alignment of the voxels and the end effector in reference to the pins. In addition, the robot can pick up the voxel and connect it to previously planted voxels. The test's components are made up of two male and two female voxels. One male and one female are fastened to the table, with a third female hovering above the ground and linked to the male. The final male voxel is placed on another table to be picked up and placed.

The UR5 robot arm from Applied Labs, Faculty of Industrial Design Engineering, was employed to carry out the actions, depicted in Figure 49. To pick up and connect the male voxel, the intended end effector is linked to the UR5. This configuration is chosen to represent the beginning of the construction of a bridge or roof. The Arduino is used to trigger the end effector, and the main function conducts all of the following activities sequentially: move down, activate electromagnet, rotate 90 degrees clockwise, activate electromagnet, rotate 90 degrees counterclockwise, move up.

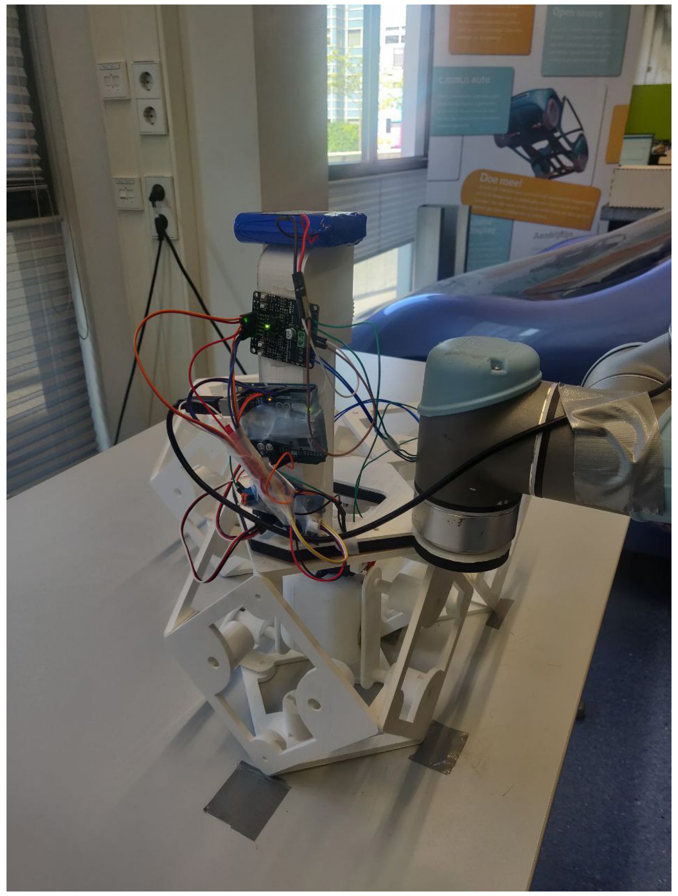


Figure 50. Test setup: interference between electromagnets and pin bridges

Another test that was conducted is the interference test between the electromagnets and the permanent magnets inside the pin bridges. Since a magnetic field is created when an electro-magnet is activated it might interfere with other pin bridges and (un)lock ones that should stay in there current position. The test's components are made up out of one male voxel with two pin bridges inserted in opposite sides. As well as an already deployed end effector such that the holder is pointing to the electromagnets in the direction of the pin bridges.

This configuration is chosen to represent the connection of a male voxel in between two opposite female voxels. The Arduino is used to trigger the electromagnets, and the main function first repels the left pin and after the right pin. This is repeated in the reversed order and last both electromagnets are activated to see if both can be reppeld at the same time to improve assembly time.

5.3 Requirement evaluation

Evaluating the requirements will help determine whether the concept is technically possible and highlight any gaps that must be addressed in following versions. Tables 13 and 14 provide the results of an analysis of the connection and end effector requirements using the legend below. If a requirement is met, no further enhancements are required. If a requirement is intermediate, some adjustments are required. If the requirement fails, the prototype does not yet support it.

Legend: Met Intermediate Failed

Table 13. Requirement evaluation of the end effector

Subsystem	Requirement	Evaluation
Accesibility	The end effector should be able to access the inside of the voxel	Met
	The end effector should be able to access the connection system	Met
Connection	The end effector should be able to connect a voxel with only 10 movements	Met
	The end effector should be able to align two neighbouring voxels	Intermediate
Movement	The end effector should be able to hold the voxel while the robot moves	Intermediate
	The end effector should be able to rotate the voxel	Failed
	The end effector should be able to remove the voxel horizontally	Failed
	The end effector should be able to place the voxel horizontally	Intermediate
Electromagnet holder	The holder should be able to rotate 90 degree	Met
	The electromagnets should be able to be activated seperately	Met
	The electromagnets should have an attracting and repelling stand	Met
	The electromagnets should repel to connect the voxel	Met
	The electromagnets should atrract to disconnect the voxel	Intermediate

To meet all of the conditions listed in Table 13, the end effector requires some additional work. Due to the usage of magnets to pick up the voxel and the UR5 being difficult to calibrate, a couple of the requirements are intermediate or failed. As a result, the voxel's alignment, placement, and movement criteria are all intermediate.
The ability of the end effector to rotate the voxel resulted from the fact that it should not matter whatever direction the robot arrives at the correct location. Because the robot cannot rotate the voxel, it must adjust its location to place the voxel in the correct orientation. Even though it did not pass this test, it is unimportant because this test was designed to assess the capacity to connect a voxel to other voxels.
Finally, when the voxel was connected on both sides, the electromagnets could not attract the pins back, but they could if the pin system was tested without being attached to another voxel. In addition, the magnets used to align the voxels on both sides were too strong to detach the voxel after it was placed.

Table 14. Requirement evaluation of the connection mechanism

Subsystem	Requirement	Evaluation
Interconnection	The connection system should be integrated in the voxel	🟩
	The pin should be connected with only one movement	🟩
	The connection system should restrict sideways motion between two voxels	🟩
	The connection system should restrict vertical motion between two voxels	🟩
	The connection should restrict bending movement	🟥
	The male pin holders should not interfere with the strut clearance of the voxel	🟩

Except for the restriction on bending movement, the test meets most of the connection requirements. That it still disconnects after a force is applied is significant because the robot should be able to walk across a bridge during assembly without the voxel separating due to bending.

5.4 Results & Discussion

The test was run five times in a row to find any mistakes that would arise in every scenario or over time. From picking up the voxel to traveling back after connecting the voxel, all steps are taken into account. These findings were evaluated in order to draw some conclusions about the four steps of the test.

1. Pick up

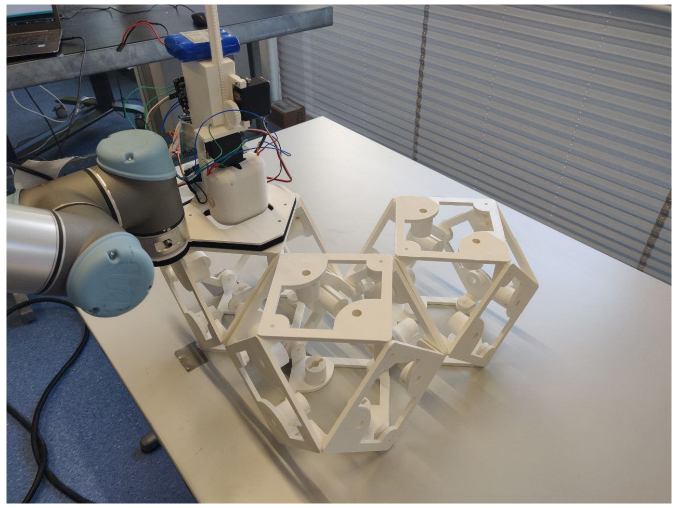


Figure 51. End effector picking up a voxel

1.1 Result

In Figure 51 it can be seen how the end effector picks up a voxel. Because the submodules have two magnets on each side for alignment, the end effector used two magnets to pick up the voxel. As a result, the robot could pick up a voxel without it having to be perfectly in place, and it did not drop the voxel in any of the five tests.

1.2 Discussion

While the UR5 was holding the voxel, it was noticed that it was wiggling excessively, giving the impression that the robot would drop the voxel. In practice, the end effector should use at least two grabbers to take up the voxel. The grip between the voxel and the end effector can thus be modified such that it is stable while the robot is moving and easy to release the voxel after placing it. Only when making use of grabbers the ease of alignment should be created with the use of sensor feedback since now the alignement of the magnets is lost.

The simple notion of employing magnets to pick up the voxel worked effectively because it was strong enough and did not require precise alignment. This aids in system simplification but may not be the optimal approach for employing these robots in unsupervised circumstances.

2. Placement

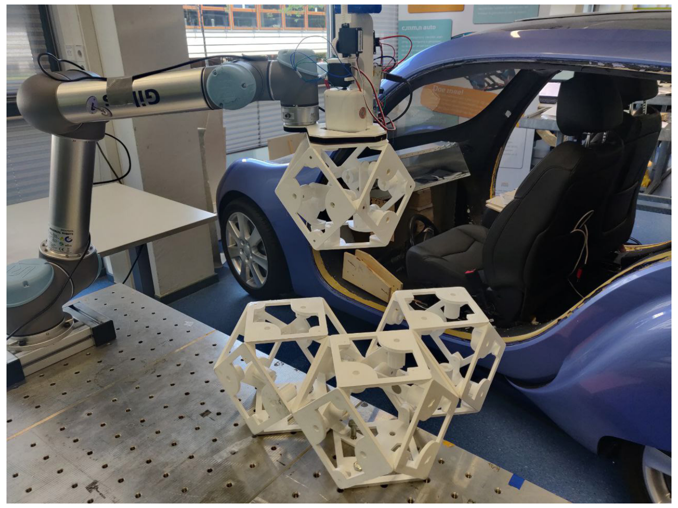


Figure 52. End effector placing a voxel

2.1 Result

In Figure 52 it can be seen how the end effector places a voxel. Once the proper movement and alignment were calibrated, the UR5 could easily place the voxel in all five tests.

2.2 Discussion

Some challenges occurred while positioning the robot to place and align the voxel. It was tough to align the voxel with the two female voxels since the UR5 does not allow any movement when it reaches one of its waypoints. In addition, due to the voxel wiggling, the UR5 had to travel down and sideways at the same time. The voxel repeatedly collided with another voxel, resulting in the voxel dropping and fracturing or the UR5 halting.

Magnets, on the other hand, were demonstrated to be a promising feature. When one of the voxels came close to the other two, they drew it into place. As a result, if the crawling robots are as pliant as envisioned, these magnets will aid in voxel alignment without requiring the robot to be exact, simplifying the robot.

3. Connection

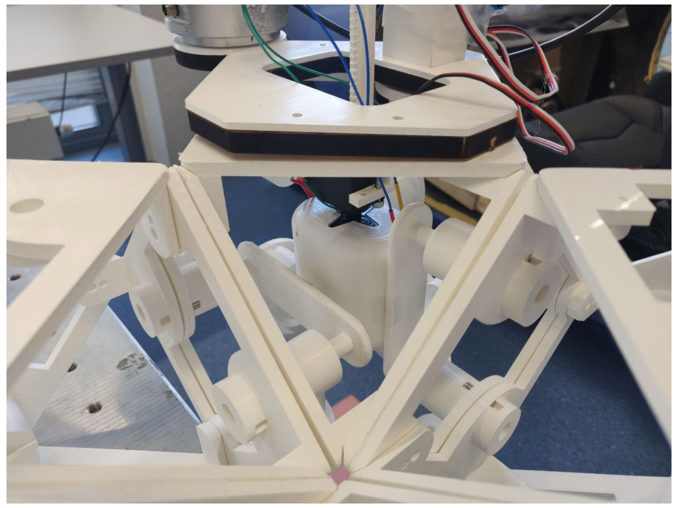


Figure 53. End effector connecting a voxel

3.1 Result

In Figure 53 it can be seen how the end effector connects a voxel. Setting both servos to their original positions produced the proper alignment for moving the pins and connecting the voxel. Nonetheless, the servos grew in inaccuracy with time, necessitating a servo correction prior to the third test due to calibration difficulties.

3.2 Discussion

The end effector has to connect the male voxel to both female voxels after placing the voxel. The problems were caused by the imprecise servos utilized in the end effector. It was difficult to calibrate the continuous servo so that the electromagnetic holder moved down by the same amount it moved up.

The first servo utilized for rotation has a maximum rotation of 180 degrees. The issue with this servo was that when it required to rotate 90 degrees counterclockwise, it couldn't get into the appropriate position, resulting in an oscillation that caused a constant vibration throughout the entire end effector. The vibration problem was addressed by replacing the servo with a continuous one, but the same error happened as with the other servo and had to be manually adjusted after the third test.

Although the servo was not very accurate, they were able to orient the holder so that the pin could be moved. This demonstrates that the concept has the potential to function if improvements are made and might thus be employed in practice in the future because it will produce an overall cheaper and faster way to robotically assemble cellular structures.

4. Release

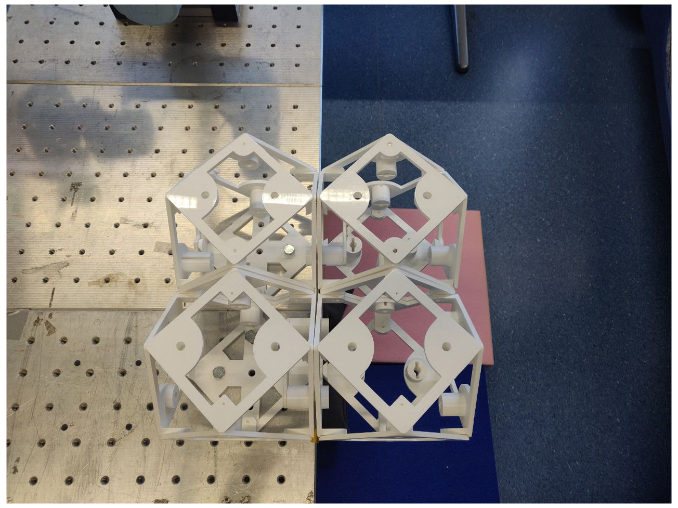


Figure 54. Placed voxel

4.1 Result

Figure 54 shows how the end effector has released a voxel. Despite the fact that the voxel was held in place by magnets on the end effector, this connection system was strong enough to maintain the voxel in place when the robot moved away to pick up the next voxel. Throughout this phase of the test, there were no complications, and the voxel remained connected to the voxels without ever falling to the ground.

4.2 Discussion

When the robot releases the voxel, it should travel away from the structure without causing any damage. Currently, the magnets in the end effector cause some upward bending in the structure, which is undesirable since it may cause structural damage when the placed voxel is released.

The inserted voxels stay put, however applying a force to the outer edge of the floating voxels leads them to separate after a while due to bending. To avoid this failure, the pins may need to be lengthened, or the connecting system may need to clamp both voxels when coupled.

The final section of the test shows how the voxels remain connected in the absence of any upward force to support the construction. This section is important for demonstrating the feasibility of cellular structures produced by robots since gaps must be filled and no support can be used when the robots walk over these floating voxels. Furthermore, the magnets in the end effector do not easily release the voxel, which means that there will be no uncertainties when the system is utilized in practice because they will be replaced by a gripping mechanism that removes that problem.

5. Interference

Figure 55. Interference test Left: Unlocked pins Right: Locked pins

5.1 Result

Figure 55 shows how the electromagnets are capable of repelling pin bridges without their being any interference between the electromagnet and the not designated pin bridges. When an electromagnet is activated it repels or attracts the pin in front of it without any other pin moving. On top of that when two electromagnets are activated they can repel two pin bridges at the same time.

5.2 Discussion

The electromagets can be activated at the same time and sepratly without causing any interference. This proves that the design is capable of connecting voxels without causing problems as well as improving the assembly time wich improves the overall system.

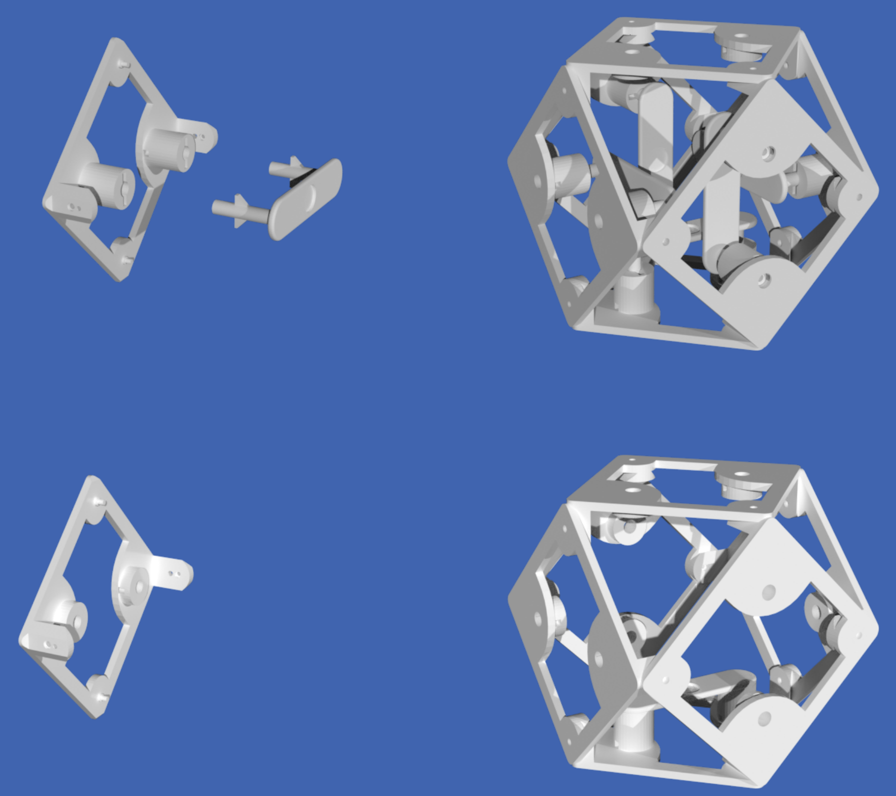
06 Final Concept

6.1 Design Proposal

The project proposes a novel concept of connection mechanism for cellular structured application. The concept is designed and developed for a combination of a male and female cuboctahedral cellular unit cell that includes a sub-module, assembled to a module, further assembled to achieve the desired geometry.

The concept is shown by constructing a cellular structure in a distant or harsh area to showcase its benefits and autonomy. by describing the interactions between the end effector and both voxels.

It also depicts the product journey of such modular lattices, which aids circular economy by allowing for easy (dis)assembly and thus permitting circular loops of repair, reuse, and repurposing.



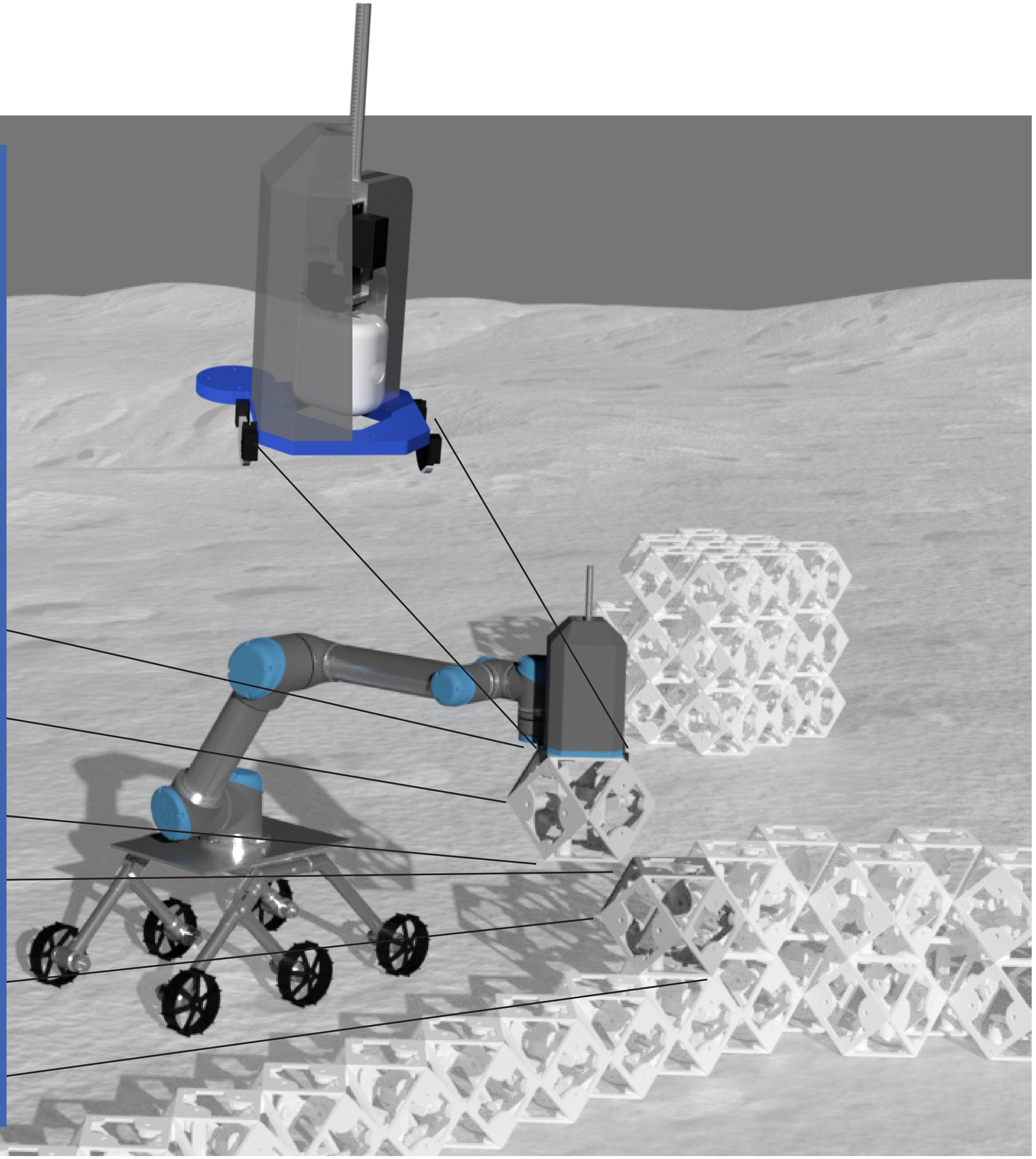


Figure 56. Design proposal: Novel connection mechanism for cellular structures

6.2 Product Journey

The main purpose of this system is to use it in harsh and remote environments which create difficult working conditions for humans. Thereby it will help humans to setup initial structures where it acts as a skeleton such that it can be worked with. It will help us explore new territory by take away high costs and guaranteeing the saftey of the workers. Currently robots are usually used to explore and provide us data, whereas now it would be possible to let the robots setup structures that would assist humans to settle at these environments.

This chapter explains how the concept of novel connection mechanism in cellular structured applications facilitates a simple robot-material system by explaining the complete product journey and where it happens, for the current concept, from manufacturing - assembly - working principle - sustainability.

6.2.1 Manufactering

Manufactering of the components for the voxels will happen at a factory were after they will be shipped to the site where the structure will be assembled. The main components to manufacture are the submodules to assembly the male and female voxels as well as the part of the end effector which should be integrated on the robot. The male submodule exist out of three parts:

1. Submodule
2. Pin

Whereas the female submodule only exist out of:

1. Submodule

And the end effector out of:

1. Platform
2. Guiding hand
3. Gear rack
4. servo holder
5. electromagnet holder

The main manufactering technique used to build these parts is 3D printing. This method was chosen due to the complex shape of the submodules, ease of prototyping, and that production waste is reduced to a minimum. Other manufactering techniques are not considered during this project due to a limit in time and resources, still they should be considered in further iterations. Since the submodules include magnets injection moulding with inserts could be a possibilty or metal casting. The parts of the end effector should not be 3D printed due to its flexibilty and extensive printing times as well as that the end effector should align perfectly with the voxels and the pins inside. Therefore materials like aluminium or metal could be considered due to their higher stiffness and the manufacterings technique to be more accurate.

For using the voxels in real life situation other materials and manufactering techniques should be considered since it would make more sence to use metals. Depending on the application they are used for, the voxel size might also be changed which depends on different factors, found in Appendix E, explored by Gawde (Gawde P. R., 2021).

6.2.2 Assembly

The assembly to the desired structure involves three major steps, one is assembling the submodules, after that assembling them to form voxels and then assembling the voxels to construct the desired geometry. The assembly plan involves a lot of repetitive steps which are all manually executed except for the structural assembly. Therefore the voxels need to be assembled before shipping them to desired location as no autonomous assembly plan has been made. Thus in near future, an attempt can be made to make an autonomous assembly possible for the submodules and voxels. However the cellular structures can be assembled by robots in-situ, providing the first step towards a complete autonomous assembly of cellular structures

Figure 57 provides the magnet configuration inside the male and female voxel, and the pin bridge which the robot can use during assembly.

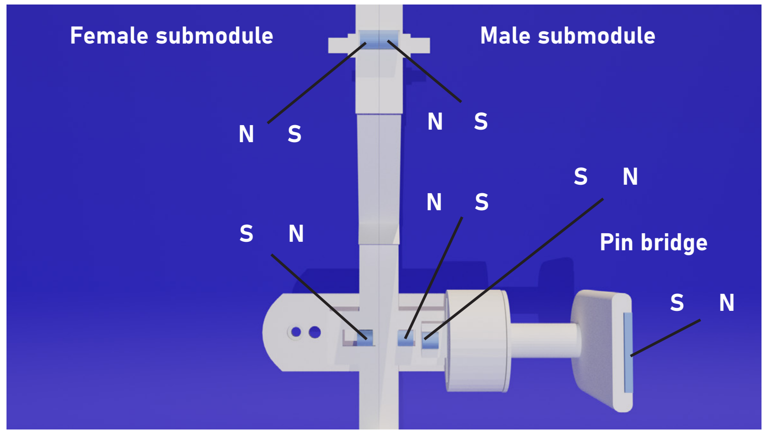


Figure 57. Overview of the magnets inside the submodules

Before the male submodule can be assembled the pin bridge should be constructed which can be found in Figure 58. The only thing required is to first press fit two small magnet inside the pins and after the bigger magnet in the backside. The orientation of the magnets can be found in Figure 57.

Figure 58. Overview of the magnets inside the pin bridge

Table 15 provides us all the steps to assemble the male submodule.

Table 15. Assembly of the male submodule

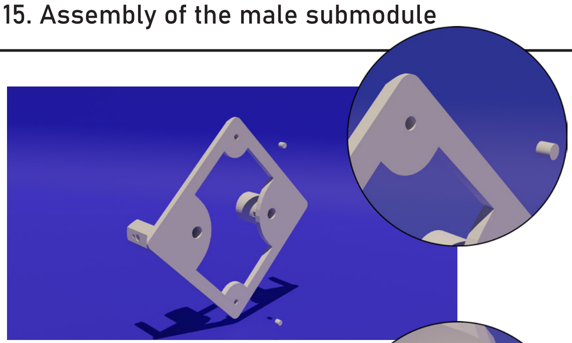
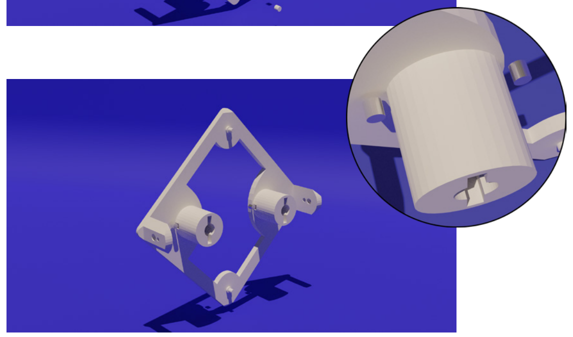
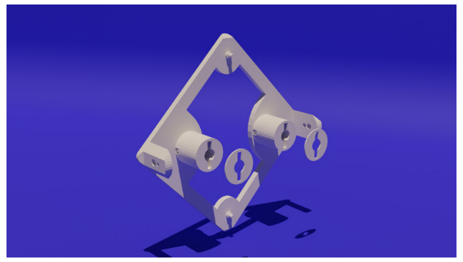
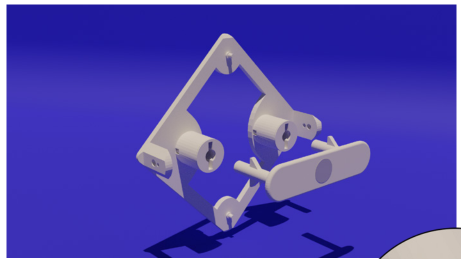
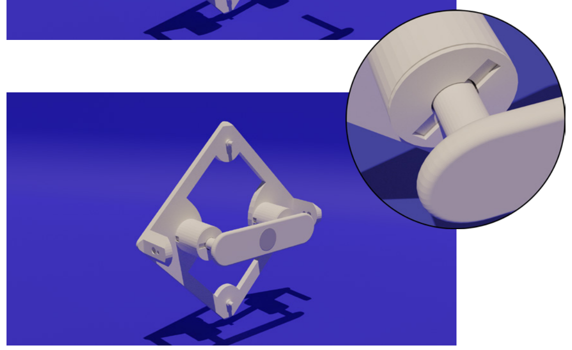
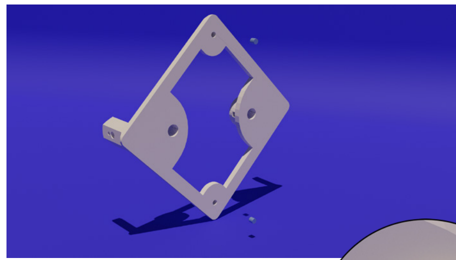
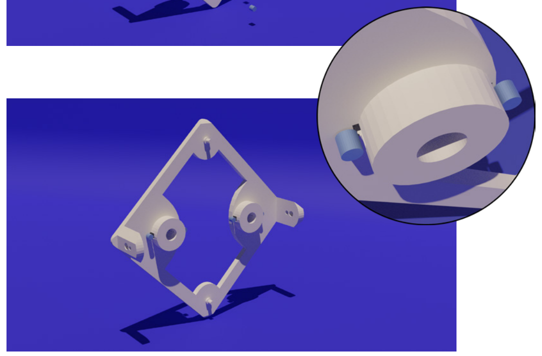
	**Step 1** Take the male submodule and two magnets. Press fit both magnets in the back of the sub-module according to Figure 54
	**Step 2** After, take four more magnets and press fit them in the pin guiders on the front side of the submodule according to Figure 54
	**Step 3** Then place two locks on top of the pin guiders before inserting the pin.
	**Step 4** Insert the pin bridge in the pin guiders.
	**Step 5** Turn the locks 90 degree clockwise to prevent the pins from falling out.

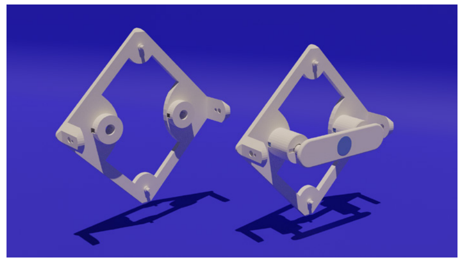
Table 16 provides us all the steps to assemble the female submodule.

Table 16. Assembly of the female submodule

	**Step 1** Take the female submodule and two magnets. Press fit both magnets in the back of the sub-module according to Figure ..
	**Step 2** After, take four more magnets and press fit them in the pin guiders on the front side of the submodule according to Figure 54

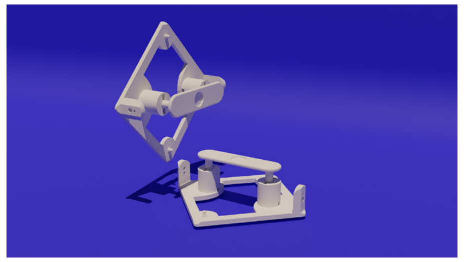
Tables 17 and 18 provide the comprehensive processes for assembling the male and female voxels. The male voxel is assembled with five male and one female submodule, whereas the female voxel is assembled with one male and five female submodules.

Table 17. Assembly of the male voxel



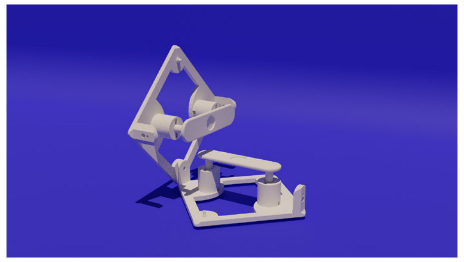
Step 1

Take 1 female and 5 male submodules and make sure all male submodules have the pin bridge inserted.



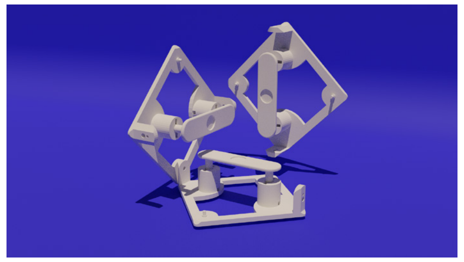
Step 2

Take two male submodules as shown. For ease of assembly, make sure the one with the dowel is placed as the base.



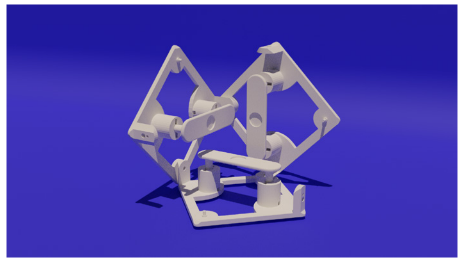
Step 3

Then coincide the peg hole of the 2nd one with the dowel of the first. Make sure the dowel is completely placed into the peg hole.



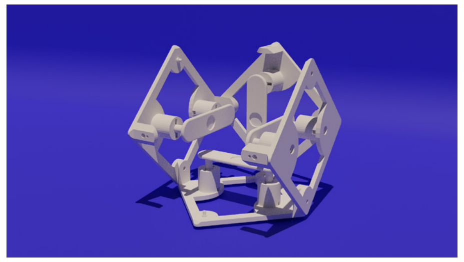
Step 4

Take a third male submodule and align its pegs and dowels with the first two as shown in the figure.



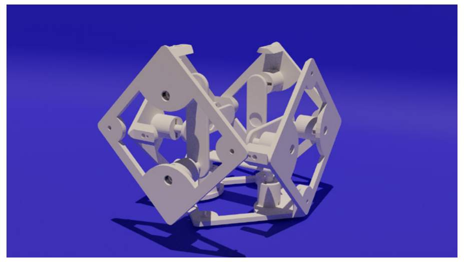
Step 5

Match the pegs and dowels and click them together to connect the three submodules.



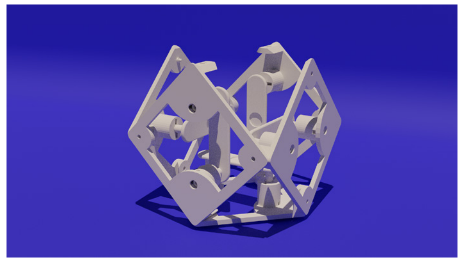
Step 6

Similarly, take the 4th male submodule and place it on the other adjacent side of the 2nd submodule. Do not mount it adjacent to the 3rd one but opposite to the 3rd one



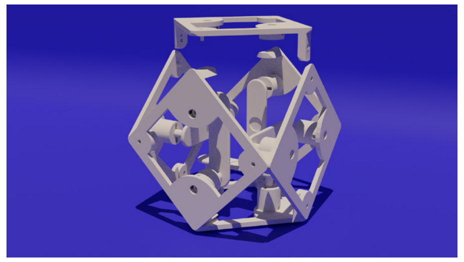
Step 7

For the 5th male module, tilt it towards the dowel of the base module and place it halfway into it. Now pull adjacent modules a bit outwards and let the peg hole match the dowels of the adjacent submodules



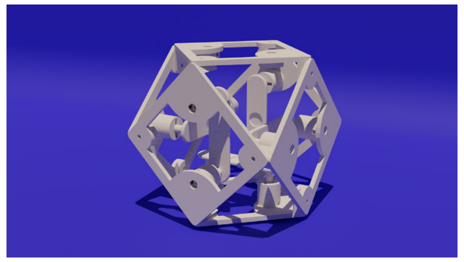
Step 8

Once all the dowels and pegs concerned with the 5th modules are aligned, click all of then together to fix the connections



Step 9

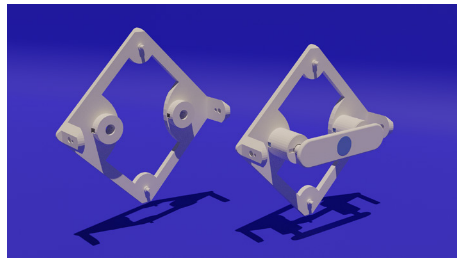
To place the female submodule, pull outwards the side submodules with dowels and align the peg holes of the last one with these dowels. Parallelly make sure the other peg dowels are also aligned.



Step 10

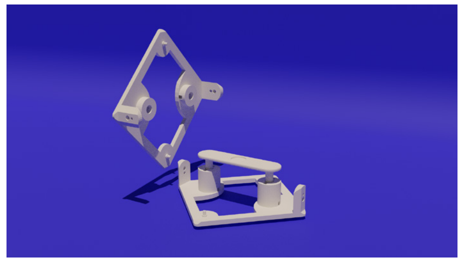
Finally, press all the peg dowels for the top together and the male module is ready. Press all the sides to ensure the connections.

Table 18. Assembly of the female voxel



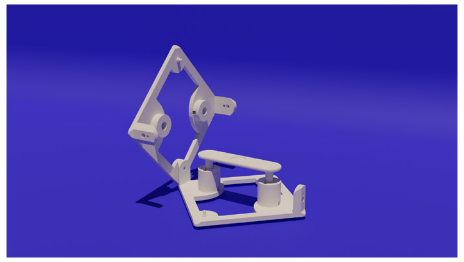
Step 1

Take 5 female and 1 male submodules and make sure the male submodule has the pin bridge inserted.



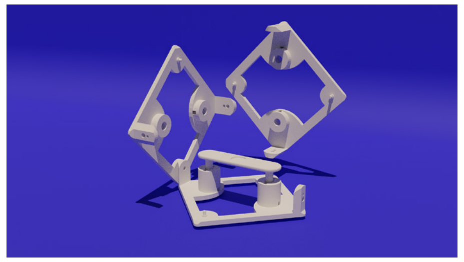
Step 2

Take 1 male and 1 female submodule as shown. For ease of assembly, make sure the one with the dowel is placed as the base.



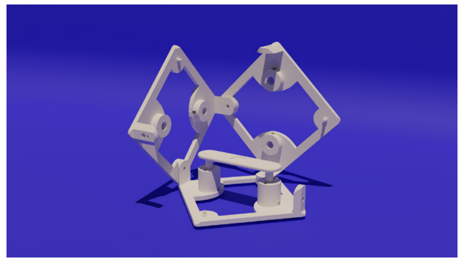
Step 3

Then coincide the peg hole of the 2nd one with the dowel of the first. Make sure the dowel is completely placed into the peg hole.



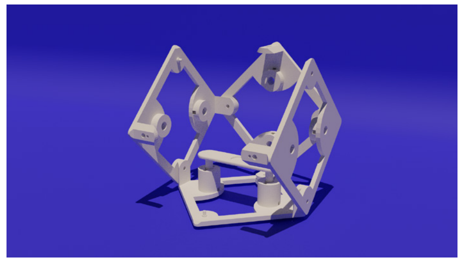
Step 4

Take a third female submodule and align its pegs and dowels with the first two as shown in the figure.



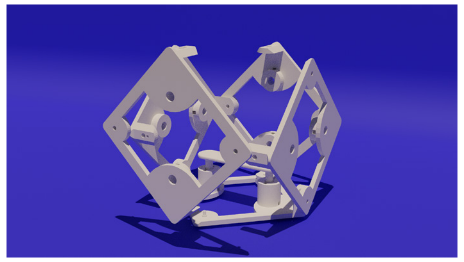
Step 5

Match the pegs and dowels and click them together to connect the three submodules.



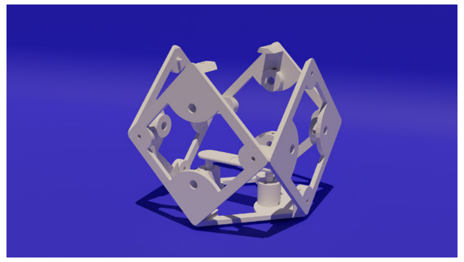
Step 6

Similarly, take the 4th female submodule and place it on the other adjacent side of the 2nd submodule. Do not mount it adjacent to the 3rd one but opposite to the 3rd one



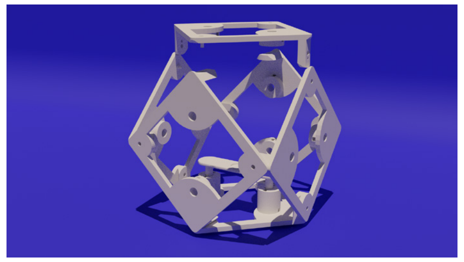
Step 7

For the 5th female module, tilt it towards the dowel of the base module and place it halfway into it. Now pull adjacent modules a bit outwards and let the peg hole match the dowels of the adjacent submodules



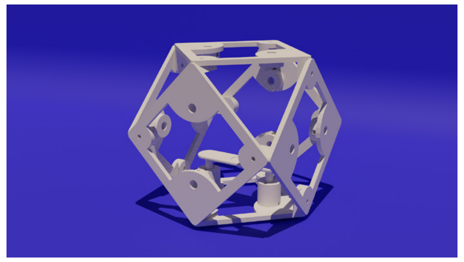
Step 8

Once all the dowels and pegs concerned with the 5th modules are aligned, click all of then together to fix the connections



Step 9

To place the last submodule, pull outwards the side submodules with dowels and align the peg holes of the last one with these dowels. Parallelly make sure the other peg dowels are also aligned.



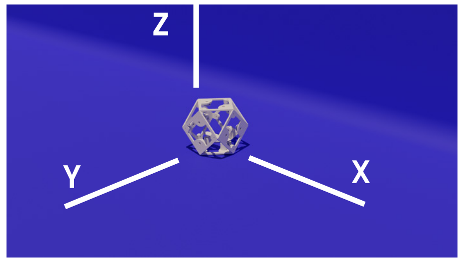
Step 10

Finally, press all the peg dowels for the top together and the male module is ready. Press all the sides to ensure the connections.

Once all of the modules are complete, they must be integrated in-situ by small mobile robots to create the needed geometry. A specific assembly pattern in regard to the end effector is established for ease of application in the robot. A UR5 was utilized due to the emphasis on the end effector and voxel connection, although the assembly pattern would be the same for the mobile robot. Table 19 shows how voxels can be stitched together by a robot without the need for inaccessible connection points. The assembly plan shown below is an example of a generic structure.

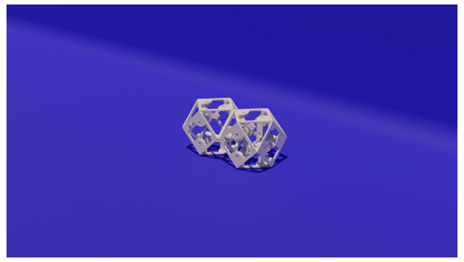
The assembly pattern is designed with the expectation that it will simplify the robots' path planning and result in a simpler voxel setup. Nonetheless, path planning and structural integrity modeling should be used to confirm this. It was not completed during this research due to a lack of time and the fact that it was not within the scope of the project.

Table 19. Automated assembly pattern that needs to be follow by the assembly robots



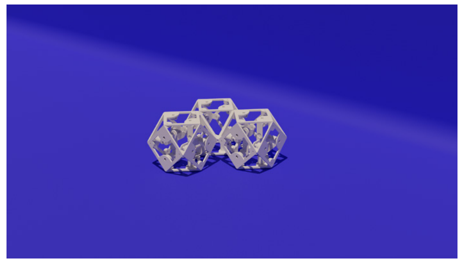
Step 1

Decide a origin point for the desired geometry. Place a female voxel at the origin position



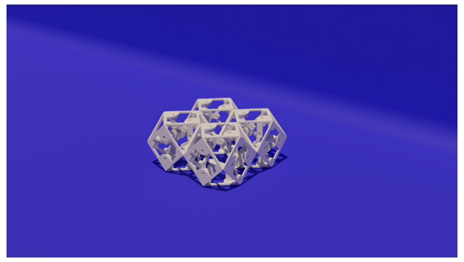
Step 2

Now decide the foundation plane (here XY) and connect the male voxel in any on the directions of the foundation place (here X). Connect the male to the female voxel.



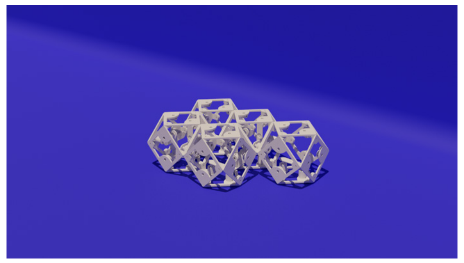
Step 3

Repeat step 2 but now in the Y-direction.



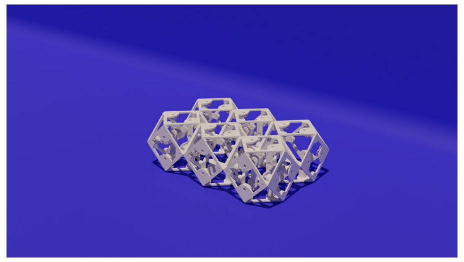
Step 4

Take another female voxel and place it between the two male voxels. After the robot should move to both male voxels and connect them to the female voxel.



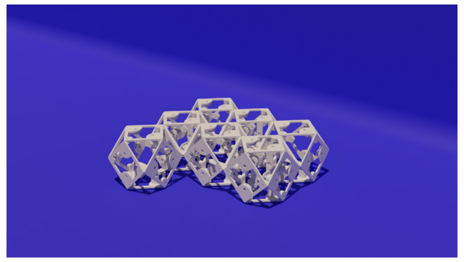
Step 5

Place a third female voxel at the boundary of the structure. After the robot moves to the voxel placed in step 1 and connects it to the female voxel.



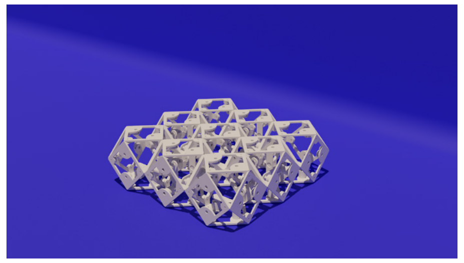
Step 6

Place another male voxel between both female voxels and connect it straight away to bot adjacents voxels.



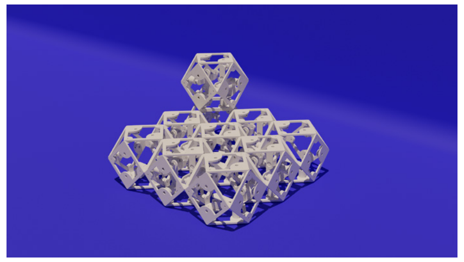
Step 7

Now continue the Y direction and connect another female voxel as shown.



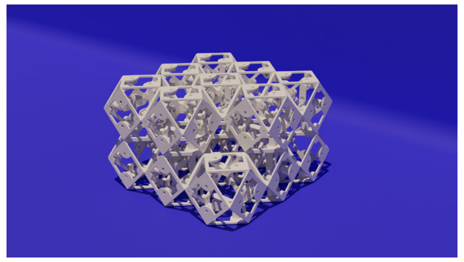
Step 8

Repeat step 2 and 5 by placing the correct voxels. Except that the male voxel has two connections and that the robot should move to the voxel placed in step 6 and connect it.



Step 9

Now place a male voxel in Z direction over the 1st voxel at the origin that we started with. Connect the bottom side.



Step 10

Repeat al steps but alter the voxels that are placed.

6.2.3 Working principle

Table 20. Explanation of the connection mechanism

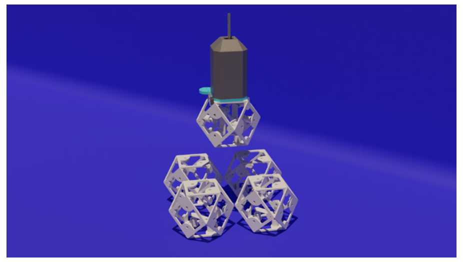
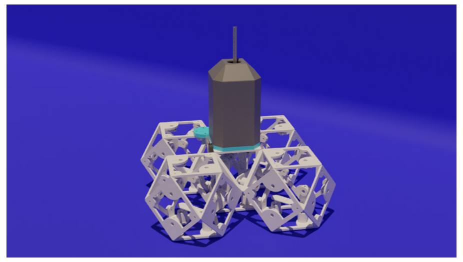
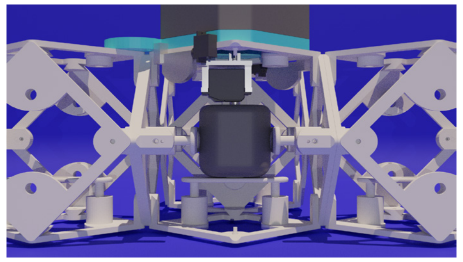
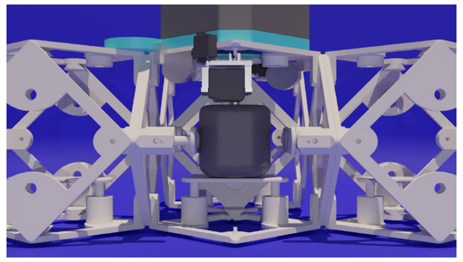
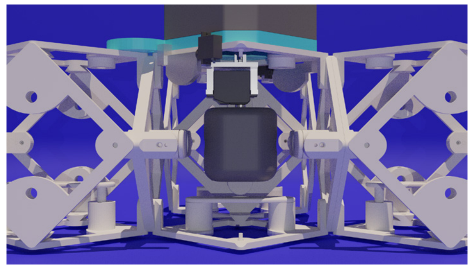
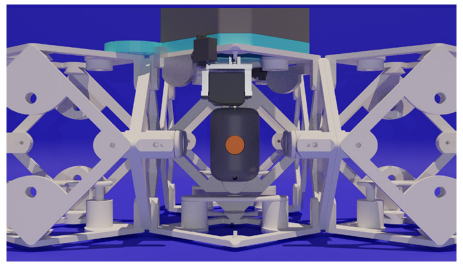
	**Step 1** The robot holds the male voxel with the end effector in the correct orientation and place.
	**Step 2** The robot places the voxel down vertically.
	**Step 3** The end effector moves the electromagnet holder straight down and aligns them with the pin bridges.
	**Step 4** The end effector will activate electromagnet 1 or 3 (here 3) to repel the pin and connect two sides.
	**Step 5** First step 4 is repeated but instead electro-magnet 1 is activated. if their is a level of voxels below, electromagnet 2 is activated to connect the voxel to the lower level.
	**Step 6** The holder is rotated 90 degrees clockwise and step 4 and 5 are repeated. After the holder is repositioned and moved upwards.

Table 20 explains how the voxels are assembled using the end effector. The end effector is shown here connecting a male voxel to four surrounding female voxels. This can be associated with linking less or the same number of voxels.

The end effector works in relation to the orientation of the robot. To simplify the working concept, it is assumed that the robot already knows where the voxels are positioned in relation to the robot's orientation. The electromagnet holder on the end effector houses three electromagnets labeled one, two, and three. Based on the robot's front orientation and the holder's ability to only rotate 90 degrees clockwise, the five sides of the voxel are assigned a body relative direction. By integrating the two, a mechanism for determining which sides of the voxel to (un)lock has been developed.

The previously planted voxels, as well as their orientation towards the front of the robot, are saved in the robot's memory. As a result, the robot understands when to spin the electromagnet holder and which electromagnets to use. Initially, the end effector may (un)lock the voxel's front, back, and down sides, as well as the left and right sides by rotating 90 degrees. Figure 59 depicts the electromagnet holder setup in relation to the robot's orientation. This approach to utilizing the robot-material system reduces the use of sensors on the robot, resulting in a relatively simple and less expensive design.

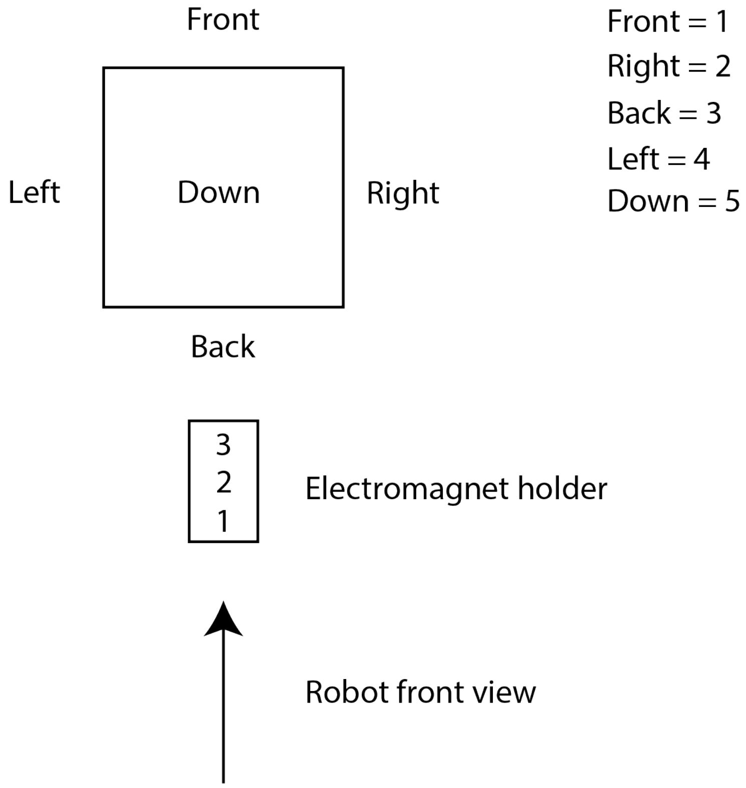


Figure 59. Voxel and electromagnet holder Top View

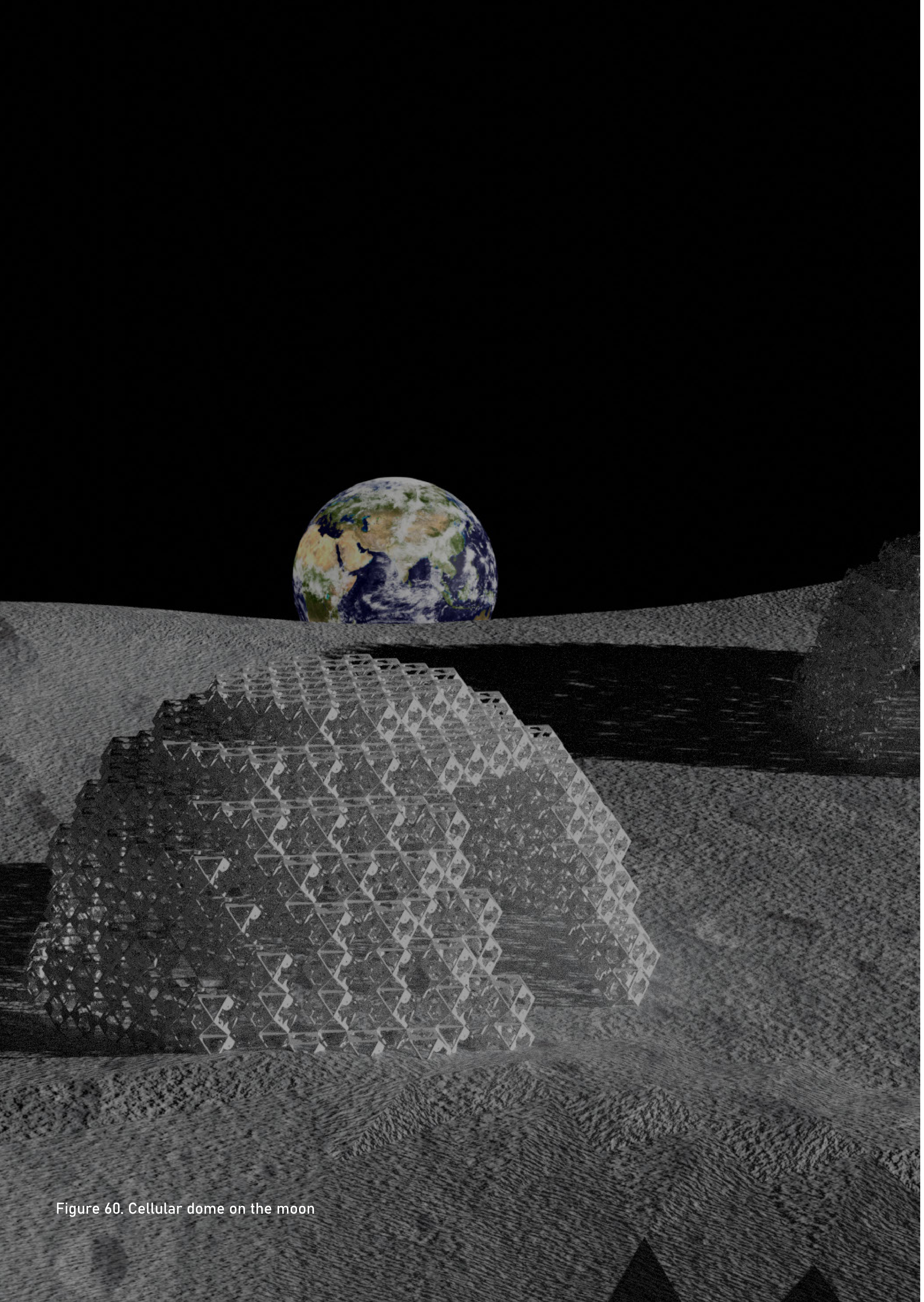


Figure 60. Cellular dome on the moon

6.2.4 Sustainability

By reducing the number of moves required to link a voxel, the project becomes more sustainable. When linking four voxels, a voxel can be joined in two motions and five actions (activating electromagnets) in the worst-case scenario. This translates into a simpler robot and resulting in shorter assembly times and a simpler system. Making the system simpler makes replacing broken robots easier and less expensive. It reduces failures, which is critical when these robots are deployed in remote and harsh environments.

The modularity of the system is now made up of a male and a female voxel. Assembly time is reduced by alternating between both voxels and using the proposed connection mechanism. Although a complete indentical system is not achieved, just two submodules must be built to provide structural modularity, which aids in repair and maintenance. This also enables designers to develop voxelized architectures, as seen in Appendix F. If modularity is not accomplished, this is not the case. Using an army of these small robots can be further simplified by assigning one team of robots to put male voxels and another team to place female voxels. This would make it even faster while also improving the chances of reusing the voxels in temporary structures.

Disassembly and reuse of the cellular structure, on the other hand, add to the system's sustainability. Because of the standardized aspects and the fact that the system does not use permanent connection techniques, disassembly will be faster as well. The capacity to disassemble the structure may enable the development of temporary constructions that may be reused in other locations or entirely changed to assemble others. All of this will contribute to a more sustainable system that will allow structures like the one shown in Figure 60 to be built.

07 Conclusion & Recommendation

7.1 conclusion

In this study, a novel design of cellular structures for robotic assembly was investigated so as to analyze its impact on the ease of dis(assembly) of such cellular structures.

The project proposes a novel concept of a connection mechanism for cellular structured application. The concept is designed and developed for a combination of a male and female cuboctahedral cellular unit cell that includes a sub-module, assembled to a module, further assembled to achieve the desired geometry. The concept was prototyped using FDM 3D printers, PLA material and evaluated with an actual tests validating the connection mechanism for the assembly of voxels.

This concept can be used to assemble cellular structures in harsh and remote environments such that humans do not have to take unassaccery risks which can be here on Earth or even in outer space. The concept was demonstrated by attaching the end effector to a UR5 and letting it connect a voxel without any upward support. The key findings of this project are stated below.

- The concept introduces more parts in the voxels but helps the make the overall robot-material system simpler creating less risks.

- The simple connection mechanism reduces assembly time creating possibilities for the robot-material system to be used in urgent situations.

- The concept shows the possibility of connecting voxels with only two degrees of freedom reducing the points of failure and making the system more reliable when used in remote evironments

- The concept is able to connect voxels by stopping movement adjacent to the neighboring voxels still a pulling or bending force could disconnect the voxels.

7.2 Recommendation

For specific requirements, the proposed concept of a novel design of cellular structure in combination with its robotic end effector for the cuboctahedral unit cell was prototyped, tested, and shown. However, the concept must be evaluated for all of the criteria of that specific application. The following are some potential improvements to the concept:

Modification to make the connection stronger between voxels

The current connection between the voxels allows the robot to easily (dis)assemble cellular structures and prevents the voxels from moving apart when a force is applied. However, the connection does not limit a pulling or bending force, which could be addressed in future iterations. It is critical that bending forces do not separate the voxels because the robot must be able to travel over voxels with no upward support when constructing bridges or roofs.

Modification for the end effector to make the robot smarter and system simpler

The end effector has all of the properties required to connect voxels, but additional features are required to improve the system. Currently, the robot must arrive in the correct orientation in order to insert the voxel with the proper alignment. To overcome this constraint, it is advised that the end effector be able to spin the voxel independently of the end effector. As a result, the direction of the robot is irrelevant while placing voxels, reducing assembly time even further.
The robot, on the other hand, receives no feedback during the entire process of inserting a voxel. It is advised that some sensors be integrated to notify the robot that the voxel is linked to the end effector, appropriately oriented when put, and connected. The servos must be changed with more accurate ones so that errors do not occur over time, or sensors must provide input so that the robot knows when the servos are in the correct position. This is one of the most significant aspects since it was discovered that if the alignment was slightly incorrect, the electromagnet would not be able to attract or repel the pin bridges precisely.

Further research for the integration of the end effector on the crawling robot

When linked to a UR5 robotic arm, the end effector concept has been proven to work. This will not be the case in real-world scenarios where the robot must move on top of the structure. As a result, it should be investigated how this end effector might be integrated into the mobile robot's current design to improve the entire system. By making the robot less stiff, such as the UR5, it may be possible to align the voxel more easily and without the requirement for precision.

Introducing a foundation layer in the cellular structure

The current design is comprised of two sorts of voxels that are only needed during assembly. If a robot begins to build a bridge and needs to cross a gap, it will generate momentum, causing the structure to tilt because it is not attached to the ground. A new form of voxel should be created with the function of linking the entire structure to the soil it is built on, allowing the structure to be self-supporting. This is an important part of the robot-material system since it must hold the robots during their lives and perform their job.

7.3 Future use cases

Today, the scale, cost, and performance of engineering structures and systems are driven by technology, materials, and highly skilled humans. Nonetheless, it does not change the fact that huge, high-performance structures are difficult and expensive to construct. Due to their lightness, modularity, and reconfigurability in construction, discrete cellular lattices may be an excellent choice in this instance.

Cases

The cellular structures could be utilized for a variety of purposes. First, selecting whether the structure will be temporary or permanent might have an immediate impact on the use case. Permanent structures would benefit workers by developing an initial skeleton construction that may be utilized as the basis. As a result, after the foundation is laid, the workers will be able to plan how they will add to and finish the construction. This will save time and money while also ensuring the safety of these workers. It can be selected whether the construction is finished or whether certain voxels are left vacant so that extra space can be added to the already built foundation if necessary.

Another application could be to aid in the 3D printing of houses on the moon or on Earth. The European Space Agency is already working on 3D printed lunar habitats made of lunar material. (ESA, 2013) Because 3D printed structures require support, they take a long time to print. As a result, using these cellular structures as support to print the appropriate shape could be exciting. So that once the print is finished, these supports can be removed and reused.

Still, having a structure to hold things in place, such as antennas or other non-habitual tasks, might be useful at times. These buildings can be constructed with voxels and then utilised in this manner. The structure does not require any post-processing to be useful. This use case may be one of the most interesting ones because it applies to all of its functionalities. It will always be modular such that the shapes can be changed while maintaining its function. It will be reusable if the objectives are met, and it will be simple to maintain as a mobile robot because the voxels will be exposed.

In addition to the recommendation, these cases may be of interest for additional research into design and learning how humans could benefit more from the cellular structure than they currently do.

My question to you is:

When shall we start building?

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