Faculty of Architecture, CTU in Prague, Department of Design Modelling

Dissertation

Building Robotic Systems

Design of a Self-reconfigurable System with Shareable Actuators

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Jan Petrš confirms that the thesis was developed on his own.

Jan Petrš potvrzuje, že práce byla vypracována jím samostatně.

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i. Abstract

This doctoral thesis investigates architectural building systems based on self-reconfigurable discrete blocks drawing from principles established in mobile, modular, and soft robotics. This thesis discusses reconfigurable and automatized architecture supported by architectural manifestos and contextualized contemporary design approaches. Necessary self-assembly, self-organization, and self-replication are described towards application in architecture accompanied by examples originating in nature such as molecular self-assembly and swarming systems. The last part of the theoretical part presents an overview of state-of-the-art modular robotic systems, mobile assemblers, mobile builders, and soft robotics.

The experimental part describes the design and development of a self-reconfigurable system, MoleMOD, an approach for creating modular robots with innovative shareable actuators. This system is based on a reconfiguration of passive discrete elements using low-cost robots able to be shared between modules and able to be configured into 2D/3D structures like modular robots. In modular reconfigurable robot systems, individual blocks can reconfigure themselves into a wide variety of forms through local interactions. Typically, each single element is mechatronized. MoleMOD's goal is to significantly reduce the high price and complexity of state-of-the-art modular robots by sharing a low number of mechatronic parts in form of novel robots using soft actuators. The concept anticipates the potential of reconfigurability in life-cycle management in which one system can achieve assembly, reconfiguration, and disassembly with minimal waste.

ii. Keywords

Distributed robot systems; Modular reconfigurable robotic systems; Mobile robotic systems; soft robotics; Adaptive architecture; MoleMOD; Smart materials and structures; Emergent systems

iii. Abstrakt

Disertační práce zkoumá architektonické stavební systémy založené na samostatně rekonfigurovatelných diskrétních blocích využívajících principů mobilní, modulární a měkké robotiky. Práce diskutuje rekonfigurovatelnou a automatizovanou architekturu. Ta je podpořena architektonickými manifesty a přístupem současného designu. Samosestavitelnost, samoorganizace a samoreplikace je popsána ve vztahu k jejich aplikaci v architektuře společně s principy, jako je molekulární samosetavování, inteligence hejna, či samoreplikující se stroje. Poslední částí teoretické části je přehled nejmodernějších modulárních a mobilních distribuovaných robotických systémů a měkké robotiky.

Experimentální část zahrnuje vlastní návrh a vývoj samorekonfigurovatelného systému s názvem MoleMOD. Ten představuje nový přístup v podobě modulárních rekonfigurovatelných robotů se sdílenými aktuátory. Tento systém je založen na rekonfiguraci pasivních diskrétních prvků nízkonákladovými roboty, které lze sdílet mezi moduly a konfigurovat je do 2D / 3D struktur podobně jako to dělají modulární robotické systémy. V modulárních rekonfigurovatelných robotických systémech lze jednotlivé moduly překonfigurovat do nejrůznějších forem prostřednictvím lokálních interakcí, kde je obvykle každý jednotlivý prvek plně mechanizovaný. Cílem MoleMOD je výrazně snížit vysokou cenu a složitost modulárních robotických systémů sdílením nižšího počtu mechatronických dílů a částečně nahradit tuhé mechanismy měkkými aktuátory. Koncept se uvažuje jako životní cyklus stavby, kdy jeden systém může provést montáž, rekonfiguraci a demontáž s minimem odpadu.

iv. Klíčová slova

Distribuované robotické systémy; Modulární rekonfigurovatelné robotické systémy; Mobilní robotické systémy; Měkká robotika; Adaptivní architektura; MoleMOD; Inteligentní materiály a struktury; Emergentní systémy

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Chapter 1.

CHARACTERISTICS OF THE THESIS

Difference fields influence contemporary architecture, and the current context reflects this, with architecture playing a new role. Today, architecture is not simply concerned with final function and appearance, but also materials, principles, and behaviours. We live in era where approaches that previously seemed like science fiction could become true [1]. Constantly changing society and human capabilities should influence our environment, including the built environment.

High consumption of materials and human resources by the building/construction industry [2]are pushing architects to think and work on the development of new systems and materials. Architects are becoming leaders of multidisciplinary research teams [3], [4] in which the design and typology of buildings play a secondary role to new primary roles: development of materials and building strategies as well as digital tools. New materials, strategies, and tools are propelling the current building/construction industry towards a more sustainable future.

Architects are developing and launching new building/construction systems and materials, with architectural designs consisting of elements capable of adapting and organising and assembling themselves [1], [5]–[9]. The author of this dissertation is contributing to this process by considering both adaptivity and sustainability through the lens of self-reconfigurable robotic systems that can automate the building process, reuse materials, adapt to their environments, and solve various problem scenarios. Imagine simple LEGO blocks that can assembly themselves into any structure needed. How can such blocks be optimally designed, and how can they be made with an eye towards sustainability? This dissertation aims to answer such questions.

1.1 Defining the research goal and thesis structure

The diagram below describes the process of research goal definition for this dissertation, divided into 5 levels.

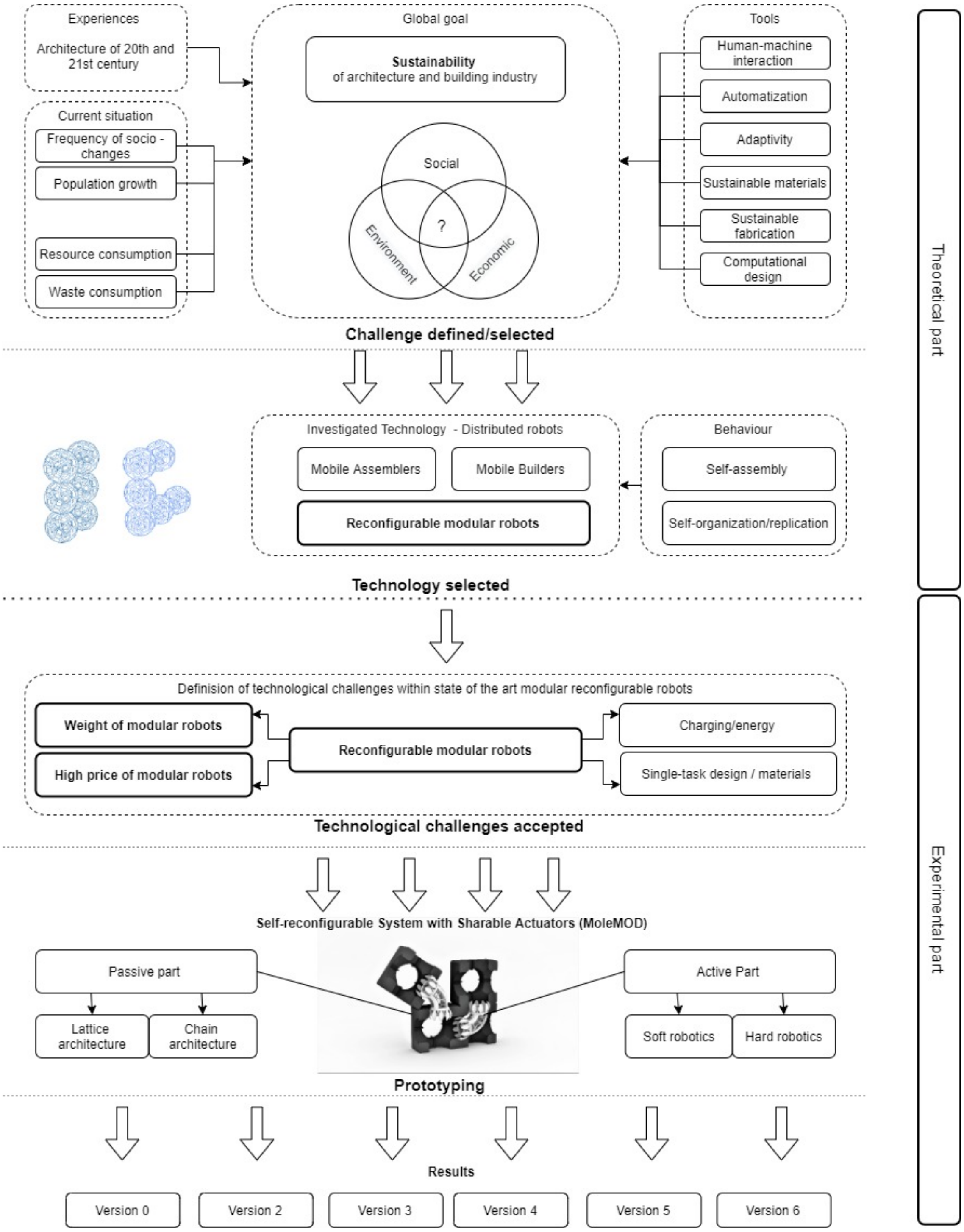


Fig. 1. Defining the research goal and thesis structure.

1.1.1 Global goal

This level defined the main points considered regarding the future of sustainable architecture. The inputs selected, the foundation for the more detailed goals of the dissertation, include changes in society, population growth, high resource consumption, and waste production coming from the construction industry. Such goals were compared to relevant developments in architecture from the 20th and 21st centuries. The tools through which sustainability, adaptivity, computational design, and automatization can be achieved were identified, which led the author of this dissertation to focus on technological solutions through which sustainability is achieved by reusability of materials and automatization.

Global goals are discussed primarily in Chapter 1 and 2.

1.1.2 Investigated technology

Distributed robots were found to be an excellent base for studying and exploring the global goals. State-of-the-art robotic projects were selected, evaluated, and divided into three groups: *Modular reconfigurable robots, mobile assemblers* and *mobile builders*. To achieve the highest versatility, adaptation, and reconfigurability in architectural implementations, *modular reconfigurable robots* were found to be the technologically most feasible solution. Emergent systems were studied in parallel, with the most relevant principles identified being self-assembly, especially self-assembly behaviour on a molecular scale.

Chapter 3 and Chapter 4 as well as part of Chapter 5 are devoted to in-depth discussions of robotic systems.

1.1.3 Definition of technological challenges

Since modular robots were selected as the subject of technological investigation, their features were compared, considering their applicability to architecture. This analysis shed light upon their weak aspects, primarily high price tags and weight stemming from mechanisms accommodated in every module. For large-scale architectural applications, many modules would need to be integrated. This would cause prohibitively high cost and weight for an overall large-scale system. To overcome such limitations, the author came up with the idea of sharable actuators.

Chapter 6 discusses technological challenges and possible solutions.

1.1.4 Prototyping (evaluation)

The ideas gathered in the course of initial investigations were evaluated through physical prototypes and computer simulations. Physical protypes uncovered details that would have been difficult to discover using simulations. The MoleMOD concept, a reconfigurable system separated into active and passive parts, was prototyped. Six versions of MoleMOD were developed. Each variation brought with it new inputs for evaluating and creating the next versions, which were evaluated and compared to other state-of-the-art project.

MoleMOD prototyping is described in Chapter 7.

1.1.5 Research goals

The five levels of goal definition listed above helped specify the overarching goals of this dissertation:

- To test, by physical prototyping and experimentation, how self-reconfigurable modular robotic systems can be modified for use in architecture.
- To reduce the amount of mechatronic parts within modular reconfigurable systems towards cost and weight reductions.
- To assist other researchers design their own reconfigurable systems for use in architecture.

1.1.6 Research vision

Reconfigurability, as described in this dissertation, is a reaction to the frequent social changes that also influence the environments (private and public spaces) in which people live. Currently, such built environments are often demolished, wasted, and built again instead of being repurposed as needs and requirements change. Intelligent materials—adaptive, self-reconfigurable, able to self-organize and perform self-assembly—would enable rapid configuration/reconfiguration as well as permanent or slower changes. Such materials could be lightweight, safe, and reusable so that heavy and dirty construction processes could be avoided, leading to precise, environmentally friendly construction.

1.2 Hypotheses

Three research hypotheses were defined, focusing on technical solutions evaluated:

- By sharing of actuators between individual modules, state-of-the-art modular robots can be made cheaper and lighter than current systems, while functionality remains the same.
- Because reconfigurable modular robotic building systems facilitate reuse, the overall amount of materials, energy consumption, waste, and human resources used by the construction industry can be reduced if such systems are introduced in architecture.

- Reconfigurable modular building systems can reduce requirements people demand for living spaces because reconfigurable living spaces can be modified to perform a variety of functions.

1.3 Methodology

The method applied in this dissertation was *research by design*, in which knowledge was produced through the process of designing and prototyping a robotic system. This involved testing of technologies (i.e., soft robotics, electronics, 3D printing), materials (rubbers, silicone, polymers, fibre composites, and so on), and software (including Grasshopper, Processing). Testing was recorded in a “diary” of processes and fabrication methods. These methods are constantly evaluated and integrated into the design of improved versions of prototypes. The diary resulted in a description of gained experiences specific to the designs investigated and implemented. Prototypes were regularly compared to recent research in the field of distributed robotics and emergent systems. Defining the constraints for prototypes helped in the evaluation of other state-of-the-art distributed robots, particularly in terms of architectural needs and requirements. The methodology integrated multidisciplinary research inputs from outside the fields of architecture and robotics. These inputs were collected and selected in order to create and refine prototype requirements. These included, for example, the development of peristaltic motion for active parts in MoleMOD, or the conceptualization of assembly logic, built upon the folding of proteins concept.

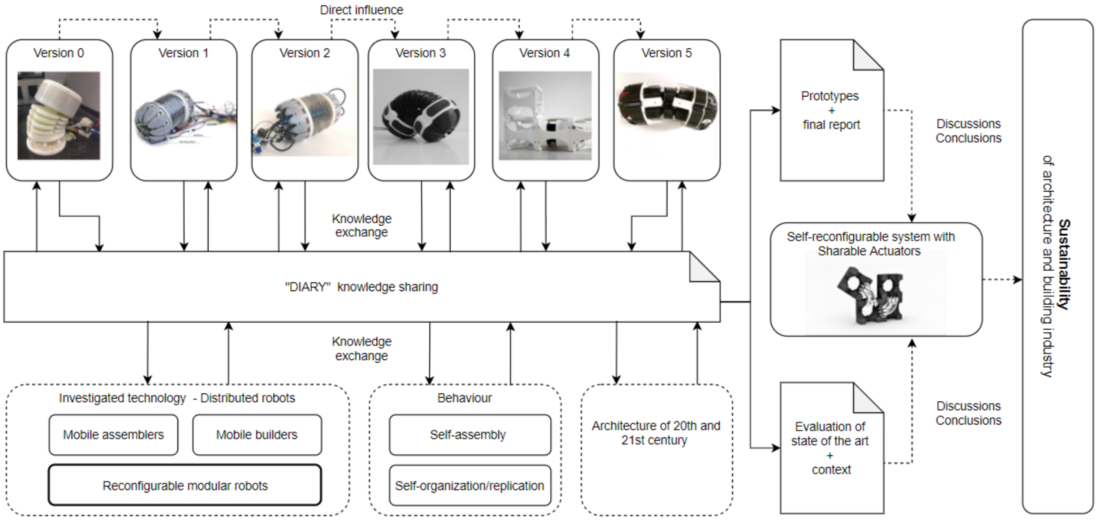


Fig. 2. Diagram of methodology.

1.4 Outline of Chapters

Each chapter discusses topics important for the design of self-reconfigurable building systems and their contextualisation within architecture.

1.4.1 Chapter 1

Defines the goals of the thesis and introduces the topic.

1.4.2 Chapter 2

Introduces selected investigations by architects in the 20th and 21st centuries, providing a strong basis of arguments that informed the direction of the research project. The architects, projects, and manifestos highlighted here were selected according their relevance to the thesis topic in order to understand what led to the current interest in reconfigurable robotic systems in architecture.

1.4.3 Chapter 3

Reconfigurable modular robotic systems behave similarly to emergent systems in nature, which they often mimic. This chapter provides an overview of natural collective processes that can be applied to architecture. The main focus is on self-assembly, the behaviour most relevant to modular robots. Processes like folding proteins, DNA machines, and many others are described, providing a unique mix of ideas for architects working on similar topics.

1.4.4 Chapter 4

This chapter evaluates and describes state-of-the-art distributed robot systems. The chapter is divided into three parts: modular reconfigurable robots, mobile assemblers, and mobile builders, with primary focus on modular reconfigurable robots. The overview of robot systems is accompanied by ideas regarding possible application to architecture. The research underlying this chapter helped in the definition of technical details for MoleMOD.

1.4.5 Chapter 5

This short chapter is about soft robotics, investigated according its use as a method of design for a sharable robot (Mole) within the MoleMOD system. The focus is on pneumatic soft actuators, which were applied to the robot prototypes.

1.4.6 Chapter 6

Describes the novel design method for modular robots developed by the author, which integrated a concept whereby mechatronic parts of a modular robot are shared between modules, essential for experimentation and robot development of MoleMOD.

1.4.7 Chapter 7

Describes MoleMOD experiments, including prototyping and simulations.

1.4.8 Chapter 8

Summarizes the thesis and discusses future developments as well as possible future applications.

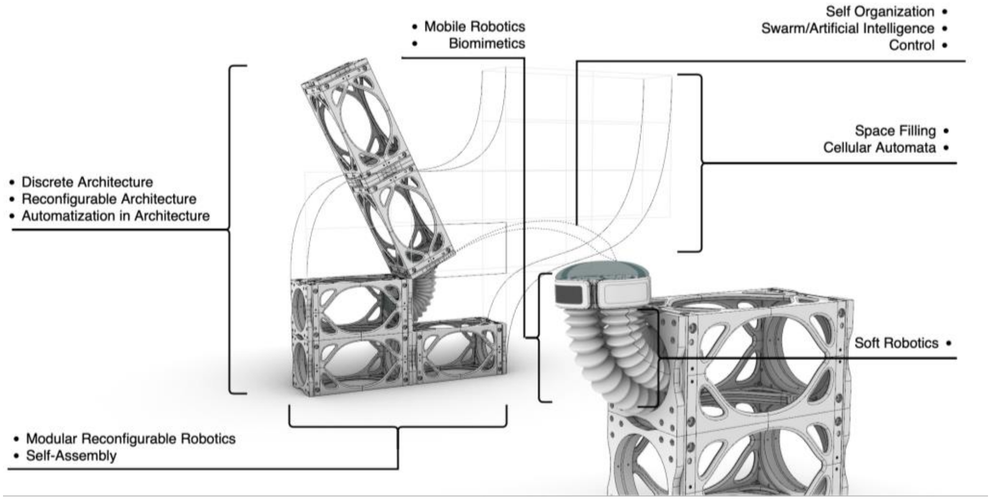


Fig. 3. Relevant topics for the concept design of a self-reconfigurable system with sharable actuators.

1.5 Scope

This dissertation was focused on design methods for creating and prototyping a modular robotic system with sharable actuators, including design, materials, and technologies accompanied by system behaviours. The dissertation was not focused on sensors, control systems, or structural analyses. The robots and modules developed were prototypes and provide the basis for further refinement and development.

Chapter 2.

20TH AND 21ST CENTURIES: TOWARDS SELF-RECONFIGURABLE MODULAR ARCHITECTURE SYSTEMS

Self-reconfigurable modular systems in the context of architecture are a relatively new topic of investigation. To some, this subject might be seem like science fiction. As far as the author of this dissertation is concerned, self-reconfigurable modular systems are a natural response to the technological boom and socio-political changes that have taken place throughout the 20th and 21st centuries. Intense discussions about sustainability and the changing technological environment have sparkled the interest of architects in adaptive systems[10]. The fluctuations of society and technological progress have triggered an interest in new materials, digital design methods, and fabrication techniques. Furthermore, these factors, over time, became limiting to architects, so they have started to develop software, materials, and fabrication methods specially designed for architectural purposes [11]. The role of architects in recent years has changed: they are more than just consumers and compositors of off-the-shelf products and are becoming visionaries and technological developers[3], [4]. The author of this dissertation calls such architects “environmental architectural engineers”. Their ambitions are usually not simply to design a perfect building in the conventional sense, but rather to develop materials, software, and methods from which a built structure can be created. Many of these contemporary architects share a common vision of a more sustainable and cost-effective architectural process. This dissertation includes an investigation of natural materials, robotic assemblers, software developments, and other related developments which are working together towards the same goal: to reduce extremely high resource consumption and pollution stemming from the construction industry [2].

This section is divided into five sub-sections that highlight technological developments towards a self-reconfigurable modular architectural process. Each sub-section will discuss the most relevant architectural investigations and related technologies.

2.1 Industrialization of Architecture

To find the origins of modular reconfigurable systems, we must go back to the Industrial Revolution between 1760 to 1820. During this period, fundamental changes in technology started which also later influenced architecture and the construction industry [12]. New materials, especially steel, began to replace bricks, wood, and stone and allowed lighter and taller buildings that subsequently, significantly changed urban planning as well [13]. The production of new built structures was no longer performed only on-site, but rather significant parts of the process began to happen in factories (off-site) [12]. With the expansion of transportation systems, especially railways, buildings no longer had to be predominantly fabricated on-site from local materials, but parts could be transported across greater distances [13]. On-site work was reduced to a minimum by using precise elements with prefabricated joints for rapid erection [14]. The fabrication and assembly processes determined architectural design. The focus was on lighter elements and materials that could be easily handled and transported, repeating/modular elements that were serially produced, and joints designed for rapid construction. Essentially everything was designed to save time. Buckminster Fuller, in his essay "4D Time Lock" [15], differentiated *design* and *industry* according to their dimensions. In a design that had only three-dimensions, this meant merely designing surfaces according to geometrical combinations. However, he saw industry as four-dimensional, with the fourth dimension being time. He considered industry to be a timesaving institution. When we look closer and compare modular reconfigurable robotic systems (discussed in Section 4.1) with architectural industrialization in the 19th century, some fundamentals are common to both. With modular reconfigurable robotic systems, in a manner similar to the architecture of that time, there is an emphasis on timesaving through modularization of goal products/buildings/structures. For both historical and robotic systems, there is a common vision: reduction of on-site assembly by means of rapid joining systems. Both Historical and robotic systems also harness the concepts of reusability/dismantling and the universality of solutions. Materials in both historical and robotic systems should be light and their production inexpensive. What is different is the perception of time in the 19th century and the 21st century. First, what was seen in the 19th century as a fast assembly, on-site process (screwing, riveting) is today criticised as slow "slavery" work [16]. Second, the first industrialized structures were planned to be dismantled only once or twice per live-cycle, while there is now a tendency to make architecture that is adaptive in real-time[1], [5], [17], [18].

The examples discussed here start with the industrial revolution and end with World War I, with the most significant building of that time being the Crystal Palace by Joseph Paxton [14], in the opinion of the author of this dissertation. Architects of that period such as F. L.Wright [19], O. Wagner [20], A. Loos [21], and many others also utilized new technologies and materials that resulted in the beginning of modernism.

2.1.1 Crystal Palace

This iconic building from the Victorian Era of England is one of the most influential buildings ever built [14]. The definition of its building program as well as the fabrication and assembly process provide excellent examples of how modularity/segmentation accompanied by perfect organization can speed up the assembly process. The Crystal Palace was designed by greenhouse designer and gardener Joseph Paxton for the Great Exhibition of 1851. The roots of the success of the Crystal Palace already stemmed from the definition of an architectural competition prior to its construction [22]. The building commission for the exhibition announced competition requirements only one year before the anticipated official opening of the selected building. These requirements included, for example, temporality, rapid erection, dismantling and expansion, and use of economical materials. The Crystal Palace was the first larger building every assembled from modular units, being 564m long and 39m high, 3,300 cast-iron columns and 2,224 principal girders supported the palace. The entire palace was erected in only 17 weeks. This was possible due to perfect organization on-site as well as certain technological developments. Joints were designed for rapid construction and dismantling employing relatively uncommon, new machine-made bolts and nuts [14]. The building site was mechanized with derricks, hoists, hammers, and drills powered by engines. The installation of nearly 19,000 glass panels was accelerated by means of carts for 80 men traveling along gutters. This enabled installation of all panels in just one week. The Crystal Palace was finished on time and opened in Hyde Park in 1851. In 1852, the palace was completely dismantled and moved to Sydenham Hill, where it was expanded. The Crystal Palace stayed there till 1936, when an unfortunate fire destroyed the whole building[14]. The building was essentially an enormous greenhouse and proper ventilation was necessary. Vents were adjusted mechanically based on thermostat readings taken every two hours. Today such principles are automatized by sensors and mechatronic systems, but the underlying venting principles remain the same [14].

Regarding the focus of this dissertation, the re-configurability of the pavilion is noteworthy. This was emphasized by the architect, Burton, who proposed that a 305m tall skyscraper be re-erected using Crystal Palace components [14]. The Crystal Palace—beyond its architecture—remains fascinating because of its construction principles, assembly strategies, and materials. This is common for contemporary architects concerned with investigating materials and fabrication principles[23]. The palace can be also understood as one of the first examples of partly automatized construction (e.g., use of carts, drills, and derricks) which is similar to the current emphasis in construction using industrial arms for partial automation [23].

The Crystal Palace is not the only one example of modular architecture influenced by the Industrial Revolution. Similar strategies were used, for instance, by Gustave Eiffel for the Eiffel Tower in 1889, or in the first iron bridge located in Telford, Shropshire (England), which opened in 1781

2.1.2 Fordism and the Assembly Line

To understand later movements in architecture towards automated building systems, the importance of standardized mass production must be mentioned. Henry Ford, at the beginning of the 20th century, changed manufacturing by introducing the assembly line. An assembly line is characterized by a continuous movement of material, usually on conveyors, through several stages towards a final product [24]. The stages of this uninterrupted process are performed by workers (nowadays, robots) repeating certain tasks. The assembly line extended the concepts of the Automated Mill by Oliver Evans and Taylor's Scientific Management theory [24]. To make production efficient, parts were standardized and interchangeable. The variability of products was defined by the limited properties of standardized parts, but the process enabled cheap and fast production of end products. Almost immediately (circa 1910), the interchangeability of parts triggered architects to be interested in incorporating the principles of serial production and standardization in order to "industrialize" the building processes [25]. The assembly line and standardization in the context of modular reconfigurable building systems can be viewed from two perspectives. The first perspective is the standardization/interchangeability of parts followed by a final product/building. For such cases, joints are designed and applied for fast and smooth assembly. The second perspective is, by contrast, a "bottom-up process" in which components are formed on-site, skipping all off-site fabrication. When reconfigurable modular building systems are understood as "materials", no machines are even needed, because such architectural systems "self-form" by themselves

2.1.3 Antonio Sant´Elia: Manifesto of Futurist Architecture

Elia articulated an explicit critique of decorative Neostyles[26]. He welcomed industrialization as an opportunity to make a new and fresh start and a way to break the continuity of architectural traditions. He proclaimed his ideas through futuristic house and city designs. Elia saw future architecture as impermanent, where historical styles are incompatible with scientific developments. He proclaimed the futuristic house to be a gigantic machine, mobile and dynamic in every detail. He called on architects to find inspiration in new materials and technologies and not to follow the old models of architecture, in which every generation built its own city [27]. More than a hundred years later, Elia's ideas still provide an important message which can be applied to the contemporary turn to digital architecture [28] and by a new generation of architectural students.

2.2 Between the World Wars

During the period between the two World Wars, the field of architecture intensively explored the idea of Modernism, while traditional craftsmanship was slowly being replaced by industrial production. The difficult economic situation and shortage of affordable housing after World War I accompanied by the Spanish flu between 1918 and 1920 rationalized the building industry [25]. Simple and fast housing developments were needed. Iconic architects like Le Corbusier, Buckminster Fuller, and Mies van der Rohe developed their masterpieces and manifestos [15][29]. Walter Gropius established the Bauhaus [30]. In 1920, the world "robot" was first introduced in the science fiction play *R.U.R.* (Rossum's Universal Robots) written by Czech author Karel Čapek [31]. Just before World War II, Alan Turing developed the Turing Machine, one of the most important inventions of the 20th century which laid the foundations for the computer and informatics disciplines which have significantly influenced architecture over the last three decades [28].

The importance of this period in terms of modular robotics is demonstrated through rationalism and the development, in Weimar Republic Germany, of the Constructional Kit (*Wohnmaschinen*) developed by Walter Gropius [25]. In the second part of this section, selected important manifestos about the flexibility of spaces and "Biotechnics/Biotechniques"are mentioned.

The belief in technology during the interwar period laid down the course of architecture for the next hundred years. Le Corbusier already, in 1929, criticized architecture: "A hundred years of new materials and new methods have made no change whatsoever in your architectural viewpoint" [29]. Sadly, the author of this dissertation would have to agree with Le Corbusier, that even two hundred years has not significantly changed the architectural viewpoint. It is important to remember that contemporary architectural style has many commonalities with the architecture of that period. The crisis after WWI triggered the need to implement new technologies.

During the writing of this dissertation, the COVID-19 pandemic situation is turning into a crisis. The digital technologies and automated systems which were just tested in recent years will now have to be fully integrated into architecture. The old modernist stereotypes will have to be extended by use of current technologies. Let's be inspired by the fresh approach of modernist architects relevant to the technological developments of their time. Our generation should not copy their buildings, but rather be inspired by their enthusiasm, defining our own architecture which we dream about, which fully integrates recent scientific developments and is as adaptive, ecological, and individualistic as our generation tends to be.

2.2.1 Rationalization in the Weimar Republic

Enthusiasm in the Weimar Republic after WWI was accompanied by bad economic conditions, which triggered an interest in industrialization and rationalization originating in the progressive United States [25]. The situation in the Weimar Republic more intensively continued the rationalization which started before WWI. One of the pioneers of the automation and systematization of the construction site was architect Martin Wagner [25]. Inspired by the American construction industry, he invented a construction method in which on-site prefabricated concrete slabs were placed using a gantry crane [25]. Even though the method reduced the number of workers, the proclaimed reduction of costs was not achieved and, due to the large size of slabs, downtimes prolonged scheduled completion times. Inspired by Wagner's work, Ernst May developed the more successful Frankfurt assembly method [25]. Success was achieved by subdividing panels and slabs into smaller formats, improving the quality of prefabricated elements and providing a higher assembly tolerance [25].

2.2.2 Walter Gropius' *Wohnmaschinen* Constructional Kit

Walter Gropius was one of the leading figures of Modernism and Rationalism as well as a founder of the Bauhaus School [30]. For the scope of this dissertation, his Constructional Kit (*Wohnmaschinen*), first introduced in 1922, is noteworthy. The Constructional Kit proposed a set of interchangeable and precise parts which could be assembled in various combinations. Two versions were developed: the "Honeycomb system" and the "Big Constructional Kit". Gropius aimed to maximize the replacement of manual workers with technology. His ideas were demonstrated through two houses: the Experimental House am Horn and the Steel House in Dessau. The idea of the Constructional Kit never resulted in mass production, mostly because = World War II interrupted its development [25].

The Constructional Kit can be associated with the mass production of prefabricated post-war housing with its negative image resulting from bad quality and its non-human scale. The principles and experiences of the Constructional Kit have the potential to be applied in robotic assembly systems.

2.2.3 Knud Lönberg-Holm

The new technological inventions of the interwar era enabled new requirements for architectural function. In 1929, Danish architect Knud Lönberg-Holm proclaimed new buildings to be "space machines" built to facilitate the free functions of humans and their social needs. Such machines, he postulated, should be flexible and always conform to the functions of life.

Holm's thoughts are very relevant and can be applied to the concept of reconfigurable modular robotic buildings, the main goal of which is interaction with flexible environments and their visitors [32].

2.2.4 Frederic J. Kiesler: Biotechnique

In 1939, Frederic J. Kiesler made a distinction between building techniques in nature (*Biotechnics*) and of humans (*Biotechniques*) [10]. He also criticised the formula "Form follows function": since functional design was introduced in the early 1920s, there were new functions being invented and evolving at that time; however, new buildings remained tied to conventional ways of living [10]. He suggested replacing this concept with a proper progression of structure, function, and form in which all functions and all forms would be contained in a structure [10]. He invented the term *Biotechnique* as a polarization of natural forces towards specific human forces. He differentiated nature and human-made building methods. While nature builds on the basis of cell division with the aim of continuity, humans can only build by joining elements together—without continuity.

Designers, according to Kiesler, should learn from the building methods of nature and minimize the number of joints. This would positively influence costs, necessary maintenance, and increase rigidity [10].

2.2.5 Karel Honzík: Biotechnics

The term "biotechnics" was first introduced by Sir Patrick Geddes. In his article, "Biotechnics: Functional Design and the Vegetable World", Czech architect Karel Honzík proposed that technology is driven by fundamental principles in a manner similar to natural processes such as sustainability and efficiency [33]. Thus, he concluded that technology is inherently ecological. Honzík gave excellent examples of the evolution of natural shapes that seldom achieve perfect forms according to their purposes. Similar to human experiments, nature struggles by trial and error before finding a final optimal shape. There are many species and variants of living organisms living under similar conditions, and it is difficult to say which one is the correct one.

Discussions about "biotechnique" and "biotechnics" later helped define "biomimicry" and gained the interest of architects in sustainability questions[34].

2.3 From World War II to the Information Age

The devastating situation after World War II triggered intensive housing needs[35]. Cities were destroyed and a large number of people were without homes, an urgent problem which needed to be solved. New materials such as aluminium, polymers, fibre composites, and so on were introduced into the construction industry [36]. New methods of fabrication were developed and new waves of fresh thinking arose. The needs were so intense that in many cities (for instance, Prague and Berlin) “unhumanistic” prefabricated housing forever changed panoramas. Construction had to be performed very quickly, which negatively influenced the quality of such buildings [25]. Post-war architecture diversified into many styles [37]. Discussions about flexible spaces, prefabrication, and the integration of new technologies were already established and their necessity was obvious, under such conditions. The exploration of virtual environments through TV and radio, the computational power of PCs, and the development of the first robots and kinetic systems began to influence architecture.

This section focuses on reconfigurable and kinetics architecture, which can reconfigure and adapt and which is mechanized, mobile, and not static. The most relevant manifestos and investigations on reconfigurable or mobile architecture of the post-WW2 period have been selected for highlighting in this dissertation.

2.3.1 Yona Friedman: Manifesto de l’Architecture Mobile

In 1956, Yona Friedman was the first person who introduced the concept of mobile adaptive architecture at the *Congrès International d’Architecture Moderne nr. 10* conference with his revolutionary pamphlet, “Manifesto de l’Architecture Mobile” [38], which proposed that architecture had the ability to create social changes. Friedman’s early work was affected by the post-WWII building boom. Friedman was not only an architect, but also an excellent urban planner with the main goal of maintaining land and using city areas for expansion [39]. He did not want to demolish old city structures and build new ones, but wanted to build new cities above already-existing structures in the form of platforms in which citizens could express their individual designs for new housing[39].

This corresponds to the idea of reconfigurable robotic systems, because in the latter, the goal is not to completely replace cities with adaptive modules, but rather optimize already existing structures by means of reconfigurable systems, thus giving them new functions or making them “clever parasites” on outdated structures that become, with the so-called parasites, contemporary.

2.3.2 Cedric Price and Joan Littlewood: The Fun Palace

In the 1960s, London actress Joan Littlewood came up with the idea of The Fun Palace.The goal of this unconventional theatre, in which visitors are actors, was to turn leisure into creative constructiveness and learning by doing[40]. The Fun Palace was not intended to be a permanent enclosure, but rather an open space that would allow for variability in the individual spaces interacted with by visitors [41]. In 1962, Joan Littlewood met young architect Cedric Price, known for his unconventionality. Cedric Price found the idea of a highly adaptive, variable, and interactive building challenging. Spaces in such a building could be used for different events with an endless variety of configurations and placement, lighting, acoustic accessibility, reusability, and ability to be dismounted In his first sketches for the Fun Palace, the building was designed as a skeletal framework [42]. Leveraging the expertise of structural engineer Frank Newby, the structural system design resulted in a pattern of different interlocking squares consisting of fourteen parallel rows of service towers with technical infrastructure, elevators, and stairs placed around a central space. Above the central space would be an overhead gantry crane which would operate over the space and move modular elements according to their interactions with Fun Palace visitors [42]. Visitors could change with their spaces, with movement facilitated by cranes manipulating prefabricated modular walls, floors, and stairs, for example. Price created a team of consultants including architect Yona Friedman, producer Robert Whitehead, psychiatrist Moris Carstairs, and cybernetician Gordon Pask[42], [43]. Cybernetics was crucial for creating the behaviour of interacting changes inspired by Von Neumann’s early mathematical theory of games [44]. The Fun Palace resembled a computer game with an array of algorithms which Pask defined as “self-organizing social biological and mechanical systems” [43]. Humans interacting with the Fun Palace would be sensored and data would be transferred to a logic flowchart program which would reassemble and move certain elements and provide feedback to the system using machine learning. Price found a small island at Mill Meads to be a perfect location for the Fun Palace, and the project was approved with the Civic Trust [42]. Unfortunately, the government changed, and after ten years of struggling with bureaucracy, Price’s decade-old project became obsolete [42]. Even though the Fun Palace was never built, it provides inspiration for contemporary architects to this day. The project was prepared in detail and was ready for implementation. It was not just a sketched vision by a visionary architect but rather a carefully designed masterpiece that inspired, for example, the Archigram Group and the Centre de Pompidou in Paris by Richard

Rogers and Renzo Piano [42]. A greatly reduced version of the Fun Palace was used by Price for the Interaction Centre, built in 1976 and demolished in 2003 [42].

Even though the Fun Palace can be considered to be a purely technological project, its main concern was people. Technology was a tool for creating an adaptive, playful environment with an aim of encouraging the struggling people of that time.

2.3.3 Wiliam Katavolos: Organic

Wiliam Katavolos was a Greek-American futurologist architect, designer, and professor at the Pratt Institute. For this dissertation, his text *Organic* from 1960, which expands the idea that a building is made from genetically engineered materials, is noteworthy [45]. Katavolos proclaimed that architects should make architecture free from traditional architectural patterns and allow structures to just happen. He suggested investigating powder or liquid materials which could activate and/or expand to required sizes and levels of rigidity. Walls would be windowed in new way, floors formed like corals, and so on [45]. Katavolos refreshed the much-criticized use of ornamentation with the idea of new patterns following stress lines. As a designer, he suggested a new chair which would, through solely multifunctional chemical reactions, vibrate, cool down, and be structurally optimized and flexible. He dreamed about architecture which modifies itself though one material system solely regulated by chemical reactions—not static, but flexible and adaptable.

Katavolos' dreams correspond with the goals of this dissertation, even though the dissertation's focus is not focused on chemical reactive materials.

2.3.4 Archigram: Plug-in City

Archigram was established in 1960 by six architects from the Architectural Association in London: Peter Cook, Warren Chalk, Ron Herron, Dennis Crompton, Michael Webb, and David Greene. Archigram's work was influenced by forerunners such as Antonio Sant'Elia [27], Buckminster Fuller [15], and Yona Friedman [38]. The group became famous for their avant-garde drawings; between 1960 and 1974, they produced around 900 of them [46]. Most of the drawings show a fascination in the rise of machines. The group also reacted to the urbanistic tendencies of that time, especially Archigram critics, represented by formalism in the outskirts of the cities. Their works often included principles of mobile and moving architecture in combination with modularity and technology as a reaction to changes in society. Archigram's ideas later inspired architects such as Renzo Piano, Richard Rogers [47], and Jan Kaplický [48].

Most relevant to this dissertation is Archigram's vision for a Plug-in City [46]. The city was conceived as a megastructure consisting of modular residential units plugged into an infrastructural core. The constantly evolving structure would include transportation as well as services and residential units serviced by giant cranes on the top of the megastructure. The city would be able to transform itself into a machine capable of constantly changing.

The Plug-in City represented a typical concept of 1960s visionary architecture which reflected an architectural fascination in new technologies. Contrary to, for instance, visions of Wiliam Katavolos Archigram as well as Cedric Price, the concept called for larger elements such as walls, living unit, beams, and windows to be adaptable, which still made constraints to the environment.

2.3.5 Nicholas Negroponte: SEEK

Nicholas Negroponte is Greek-American architect, one of the pioneers of computer-aided design, co-founder of MIT Media Lab (1985) [49], and author of the bestseller *Being Digital* from 1995 [50]. From all his investigations, the most relevant to this dissertation is the controversial project *Seek* which was a part the "Software" exhibition at the Jewish Museum in New York in 1970 [51]. It was a real time experiment in between the environment and agents. The environment was represented by several boxes (physical voxels) constantly reassembled by a simple robotic arm based on the behaviour and positions of the agents. Agents were represented by gerbils (yes, live animals) who freely moved inside an environment bounded from physical voxels. Following a program, the algorithm's arm rearranged voxels based on the programmers' prediction of the gerbil's objectives. This terrific idea turned into a catastrophe. Incorrectly sized boxes allowed the gerbils to entwine themselves with the boxes, which broke the matrix of the system. The installation ended up as an apocalyptic picture in which scared and shipwrecked gerbils were covered by their own excrement inside a destroyed matrix of boxes under a broken robotic arm [52].

The experiment used illustrated a unique principle of animal-machine cooperation and showed how important the design aspect is to intelligent systems. This awareness provides a significant warning for architects dealing with cybernetics. Without well-designed machines, programmed intelligence cannot really be proven. Based on personal experiences of the author of this dissertation, computer intelligence should follow proven design.

2.3.6 Metabolism

"Metabolism" was an architectural style in Japan investigated in 1960 by a group of architects, namely: Kisho Kurokawa, Fumihiko Maki, Noboru Kawazoe, and Kenji Ekuan [53]. The Metabolists reacted to the economical-political situation in Japan after World War II: a rapidly growing population, the necessity for replacing destroyed buildings, and high density in cities. Also of influence were the mobility of Japanese people, their belief in technology, and the Japanese spiritual culture [53]. All of this resulted in Metabolism. The style applied the concepts of flow and transformation ("metabolism") of energies in the body to the design of cities and buildings. Metabolists did not want to diversify spaces in cities (e.g., living, working, recreational spaces) and transportation. Rather, they wanted to re-examine transportation as a part of living space. They advocated the changeability of structures in which useless parts could be replaced [53].

A highlight of the Metabolists' work was at the "EXPO 70" world's fair held in the Osaka Prefecture in 1970 [54]. The master planner of the world's fair, Kenzo Tange, asked the Metabolists to design several buildings including Kurokawa's Toshiba-IHI Pavilion, Kikutake's Expo Tower, and the roof of the Festival Plaza [55] . The most well-known is Kurokawa's Nakagin Capsule Tower [53]. After 1970, the economic situation in Japan did not welcome utopian large projects. Even though the Metabolists functioned for a relatively short period, their work remains impressive and timeless.

The goals of their research correspond with contemporary tendencies to discretise and reuse architectural elements [28][56] as well as the fluctuation of changes to society, speed, and mobility, giving them relevance to the design of reconfigurable architectural systems.

2.3.7 Single-task Construction Robots in Japan

The situation in Japan in the late 70s triggered an interest in government to support industrial and research projects dealing with single-task construction robots [57]. The conditions in the construction industry were worse when compared to other technological fields, especially the growing robotics field [58]. Work-related diseases, low productivity, and poor working conditions ignited the discussion surrounding these innovations. Since the government agreed on introducing robotics into the building industry, several single-tasks robots were developed. The goal was not to produce prefabricated elements in a factory, but rather to produce elements directly on site. These robots focused only on construction and their tasks were extremely specific; for instance, pouring concrete, providing reinforcement, and performing bending. Their disadvantage was the single task approach Unfortunately, the original idea was not fully successful. Problems such as operation and navigation in real world environments arose that were much more difficult to solve on-site than in a factory. This is also the reason why some companies introduced Automated Robotic On-site Factories [59].

For the purposes of this dissertation, the author views single tasks robots to be tools which do not influence architecture but which could be a kind of substitute for workers whose tasks are continuous and whose provided work is permanent. This makes them different than reconfigurable robotic systems or mobile assemblers (discussed in Section 4.1). Considering them could be highly beneficial for initiating future strategies, methods, and technologies. Such robots have played an important role in the history of building robotic systems, especially because of the concept of relocation from the lab to the building site.

2.4 The Information Age

The Information Age began in the late 20th century as traditional economies based on methods coming from the Industrial Revolution transformed into economies based primarily on information technologies [60]. Just as the Industrial Revolution impacted architecture, the Information Age has generated questions about how to integrate digital technologies into architectural design [61]. Architecture historically has gone beyond its limits by integration of technologies from other industries (e.g., construction of ships, assembly lines). The same situation happened in the 1990s when architects started to use Computer-Aided Design (CAD) software [62] from other industries. For instance, Frank Gehry’s team used CATIA (Computer Aided Three-dimensional Software) used in the aircraft industry since 1977 for the design of the Guggenheim Museum in Bilbao [61]. Software from the animation industry such as Maya [63] was used in Greg Lynn’s early work [64]. New software opened up new architectural typologies, with freeform structures gaining popularity with architects. The implementation of parametric and generative design methods gave architects more control over their models[65]. Computer-Aided Manufacturing (CAM) is also notable; with it, architects could finally control the entire process with one information model including everything necessary for design, simulations, fabrication, and assembly [61].

The connection with CAD-CAM introduced architects to new manufacturing techniques. Architects started to use CAM technologies from other disciplines and apply CAM software for greater control. By expanding their use of digital architectural parametric tools, architects became more interested in new technologies and in integrating them into architectural projects[66], [67]. This does not differ notably from the use of new technologies over the last 70 years, as discussed above and seen in several other examples showing the "long tail" of architecture's adoption of some technologies (Fig 4). For example, in 1960, French engineer and mathematician Pierre Bezier first used the NURBS curve (Bezier curve) for modelling the aerodynamic surfaces of Renault cars[68]. Architects became fascinated by NURBS freeform structures at the end of the 1990s, almost 40 years later [28]. The use of NURBS curves by architects triggered new digital architecture directions. The first industrial robot, Unimate, was invented by George Devol in 1954. Even though its creation marked a revolution in manufacturing, in architecture, the industrial robot was firstly introduced in 2005, approximately 50 years later, by Gramazio and Kohler from ETH Zurich [69]. The first fused deposition modelling (FDM) 3D printer was developed in 1989 by S. Scott Crump [70], while in architectural research, was first applied 17 years later. In 2005, Rupert Soar with his construction group at Loughborough University built the first large scale printer for construction [71]. In recent years, the self-assembly lab at MIT led by architect Skylar Tibits (see Section 3.1) has investigated materials technologies and systems in cooperation with companies including Airbus and BMW [16]. The examples show how digitalization and technology have changed the goals of architects, and they illustrate how, in some cases, they have even turned the tables, with architects developing new materials, systems, and fabrication technologies with the potential to be implemented in the commercial sector[72].

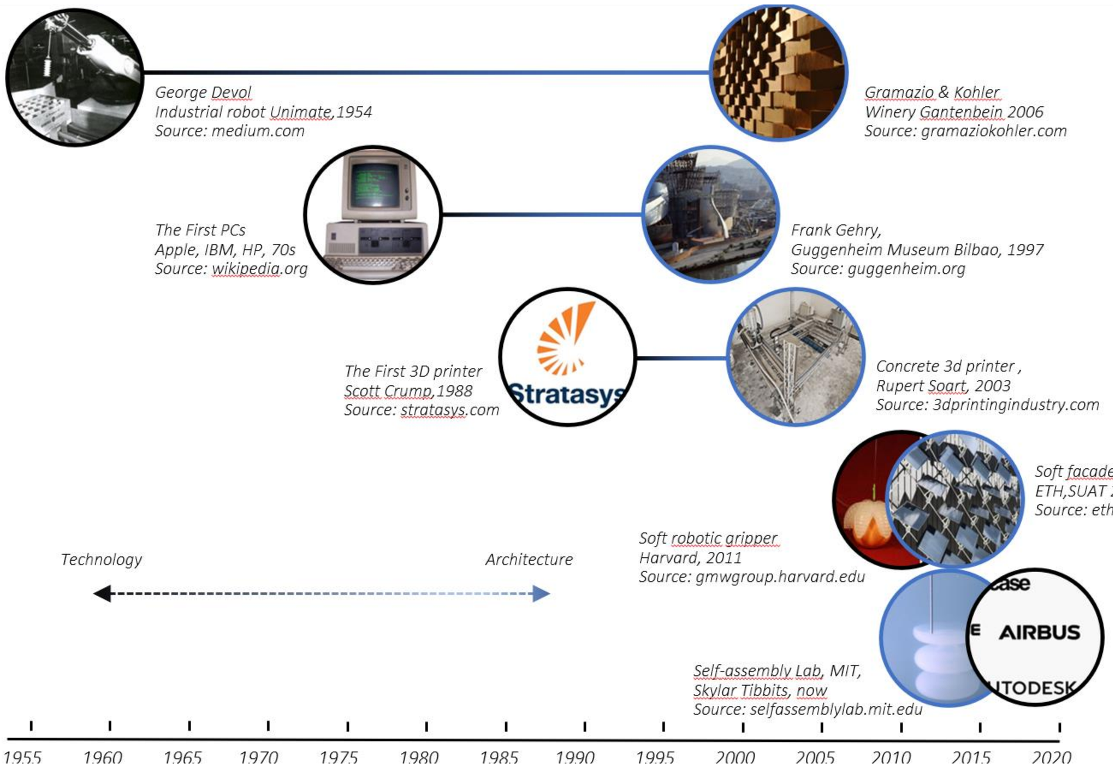


Fig. 4. Technology and its influence of architecture

Architects are also becoming leaders of large multidisciplinary research groups investigating new technologies and materials that could be used by architects [3]. The Information Age also significantly changed accessibility to education. Courses and tutorials supported by open source software and software trial versions are freely accessible using personal electronic devices. This has had the result that everyone can become a specialist without specialized education, and knowledge is gained more or less through experimentation[73]. Many architects have lost their fear of lacking knowledge from different fields. Similar to the field of music, where many excellent musicians do not know how to read music, architects have discovered that for the development of simple robots, for example, it is not necessary to know mathematics or physics laws. By simply observing and experimenting, they can reach their goals as well, with most information they need available online. Another aspect of the current environment is the accessibility of the materials, which can often be procured with inexpensive and rapid online. On top of that, open platforms such as Arduino [74] and Raspberry Pi [75] have begun distributing electronics in a user-friendly, modular fashion.

Self-reconfigurable modular building systems illustrate how already existing technology has been taken and modified not to fabricate architecture, but to *be* architecture.

Architecture in the Informational Age shows a typical symbiosis of fabrication, materials, and design [76], with these influencing each other in rather contiguous ways and are being not separated entities of a continuous design process.

The architecture of the Informational Age can be subcategorized into two periods: before and after the global financial crisis of 2008. The focus of this dissertation, however, is on post- 2008 developments in which architecture has tended to be rather discrete rather than continuous[28]. This section discusses selected architects who significantly contributed to introducing computational design to the field. Strong foundations are found in the early works of John Frazer and Greg Lynn, pioneers of cybernetics, evolutionary algorithms, digital simulation, genetic algorithm, morphogenesis, and so on—all in the context of architecture. This section also describes the contributions to the automatization of architecture by duos Gramazio & Kohler[69] at ETH Zurich and Menges & Knippers at the University of Stuttgart [77]. Finally, discrete architecture—pioneered by Carpo [28], Retsin [78], and Sanchez[79]—is discussed.

There is a long list of excellent authors, architectural schools, and research groups working in this area today. The selected topics and authors are important for contextualizing reconfigurable robotic building systems in architecture.

2.4.1 John Frazer: Universal Constructor

The importance of John Frazer for the future development of architecture lies in his contributions regarding the introduction of cybernetics and the use of computers in architecture. Even though he is from the same generation like Gordon Pask, Cedric Price, and Nicholas Negroponte [42], [80], the focus here will be on his work in the context of the Information Age. Notably, his book, *An Evolutionary Architecture* from 1995, significantly influenced next generations of architects [81]. The book describes the emulation of evolutionary processes in nature in architectural forms. The evolutionary processes in natural ecosystems recycle materials, adapt, and efficiently use energy when compared to human structures. The ecological approach does not necessarily be in copying natural structures; general principles of the environment can be applied [81]. The most interesting conceptual contribution to this dissertation are Frazer's works from the 1980s-1990s that were called "machine readable models" (including the generator project, the Self-Builder Design Kit, and the Universal Constructor)[81]. One of the most ambitious models was the Universal Constructor, a three-dimensional 12x12x12 matrix of cubes. Each cube had up to 256 states that could be displayed through 8 LED diodes. The cube faces could transfer messages about neighbouring cells as well as their own locations. The array worked as an input and output device. As an input device, the configuration of cubes and identification of them were found using information from the controlling processor. As an output device, the cubes could navigate users through displays of information statements such as “take me away” or “put next cube” [81]. The Universal Constructor was, therefore, a demonstration of a new logic for defining space guided by internal rules similar to the evolutionary processes in nature.

The Universal Constructor was conceptually very close to reconfigurable modular building systems, which are also based on their states within 2- or 3D arrays and their interaction with neighbouring modules (cells). The most visible difference is that reconfigurable modular building systems are manipulated automatically by themselves (i.e., in a bottom-up manner) without requiring an external manipulator, either human or robot.

2.4.2 Greg Lynn: Animate Form

Greg Lynn was selected for highlighting in this dissertation as a pioneer and representative of “new streamlined architecture”, established in the 1990s. His iconic book was *Animate Form* [64]. In it, Lynn explored animation and special effects software in order to define architectural forms. Using time-based animation techniques, he was able to form new plastic and free-formed structures by generating movements in animation software. In other words, Lynn used animation software not as a form of representation, but rather as a form of generation. The form finding process was performed by applying external forces to structures, by defining relations between internal constraints (for instance, “bones” and “joints“) in order to determine complex behaviours [64].

Form-finding by using external forces could help determine the final configuration of modular reconfigurable systems as well, since reconfiguration does not depend purely on its internal mechanisms and can be supported by external forces (for instance, gravity).

Lynn coined the term “blob architecture” [82], which greatly influenced the visual style of the next generation of architects. Even now, architects tend to design with curvy streamlined shapes, no matter if they are representing discrete forms of architecture or if they are demonstrating new technologies. The fascination with complex shapes still exists.

After 2000, two branches of architecture have emerged: automatization and kinetics, mostly applied to the field of architecture in reference to reconfigurable elements and to automated construction.

2.4.3 Reconfigurable elements and interactivity

When comparing current developments in reconfigurable elements to the visions from the second half of the 20th century [41], [48], [83], the movable elements have decreased in scale or have been discretized. The introduction of parametric and computational design tools has extended from solely digital movement to the physical realm. With parametric tools such as Grasshopper 3D, shapes are manually or computationally found and digitally transformed on a user's screen. Such visual interpretation of form-finding has helped to encourage the idea of reconfigurable architecture.

Fig. 5. Interactive Soft Environments – This international workshop organized by Jan Petrš and Vasilija Abramovič at CTU in Prague investigated reconfigurable discrete panels through an interactive installation

Different surfaces in the form of façades, walls, and roofs have been integrated into buildings, notably kinematic façade systems [84]. In most cases, surfaces are discretized to the individual faces reconfigured by a spectrum of actuators using either rigid mechanisms or soft actuators [85]. Façades typically then perform according to weather conditions or human positions. A similar approach is used in interactive installations (Fig.

5) in which the architecture itself reconfigures, senses, and expands an aesthetic expression, while the goal in such cases is visual titillation or entertainment rather than functional purpose. Interactive architecture is also important for promoting new technologies to architects.

2.4.4 Gramazio & Kohler: Automated construction

An industrial arm was employed for the first time in 2005 as a universal tool for creating architecture by Gramazio & Kohler [69], who focused on additive manufacturing. The introduction of new software in the 1990s (CAD) and manufacturing (CAM) was mostly dependent on CNC machines with limited features (e.g., laser sintering and laser cutting). CNC machines typically work in closed environments with specific materials in specific volumes. Industrial arms can operate in larger spaces at the architectural scale. The independence of the arm from the end effector allowed for a universality of solutions for different tasks achieved by changing end effectors. Tasks included grabbing, 3D printing, cutting, milling, welding, and spraying[86]–[88]. This differentiated industrial arms from the construction robots developed in Japan at the end of the 20th century [57]. Gramazio & Kohler's early work focused on the precise positioning of bricks according to a digital parametric model. This introduced new aesthetics possibilities for highly regular discrete bricks, which could be assembled into curvy structures[69]. In later work, Gramazio & Kohler's lab investigated 3D printing and aerial assembly with drones (see Section 4.2). Gramazio & Kohler influenced several other research groups who also employed robotic arms for digital fabrication[89].

Very soon after their introduction, industrial arms were criticised for their volume limitations and their inappropriateness for use in architecture. This triggered a new way of designing robots for architectural purposes, leading to employing rather smaller cooperative robots[90]. Gramazio & Kohler's work is fascinating and, thanks to their investigations, interest in using robots in architecture has grown and is being explored by several research groups[89].

2.4.5 Menges & Knippers: Scaling up automated construction

Cooperation between architectural researchers at the Institute for Computational Design (Menges) and the Institute of Building Structures and Structural Design (Knippers) resulted in one of the most respected research projects in the field of digital fabrication and automated construction architecture[3], [66], [67], [91]. Their ground-breaking method, introduced in 2012, used novel fibre-reinforced polymers which were wound over a structure with robotic arms on the basis of biological models supported by structural analysis of a final pavilion [91]. Menges & Knippers made use of simulation within parametric design. By tweaking and correlating design, the researchers could find an optimal shape using information coming from a simulated environment, and they considered three aspects in particular: material, fabrication, and structural design. Menges & Knippers significantly changed the scale of automated construction from prototyping to functional buildings: in 2019, they built two segmented shell structures, the BUGA Wood Pavilion and the BUGA Fibre Pavilion [66], [67].

2.5 The Second Digital Turn

The global financial crisis (2007-2008) was one of the most significant 21st century milestones for global politics, economics, and technological development [92]. In the following years, new "neo-trends" based on object-oriented geometries, so-called "post-digital" trends [78]. The financial crisis ended two decades of the field of architecture's obsession with spline defined, free shape geometries often defended by authors for their ergonomic qualities[28]. Mario Carpo, professor of the history of architecture at the University College London, described such designs as "fish" in his book, *The Second Digital Turn* [28]. Definitions of "Industry 4.0" in 2011 and 2013 triggered the implementation of automatization in architecture and soon, terms like "Construction 4.0"[93] and "Buildings 4.0"[94] started to be used—in fact, based on the similar principles as Industry 4.0[95].

For two decades, spline-based architecture used continuous data but, essentially, not in a computational way. In comparison to spline-based architecture, discrete architecture uses data more efficiently [28]. If we consider data as being free, then the use of powerful computation designs seems to be the most efficient way for building virtual and physical environments. Discrete architecture works with data represented by physical building blocks, which are accessible and versatile as digital data[96]. These discrete blocks are not defined by certain scales. Discrete architecture, for example, has been investigated at the nanoscale by Oxman[97] and Tibbits [16] (both from MIT) who are working with materials on an almost molecular scale. The city planning scale is represented by, for instance, Koehler's "mereology approach" that defines the interaction between private and shared urban spaces [98], or in computer games such as Sanchez' *Block'hood* [99].

While some argue that discretness is a method that has been applied to architecture for centuries, the methodological approach is different in its approach towards final design, the result of computational architecture freed from a human-detailed picture of the end product (e.g., building), no matter if assembled using rigorous timber elements [100] or soft inflatable pandas [101].

2.5.1 Gilles Retsin: Discrete Architecture

Retsin is a pioneer of "Discrete Architecture" who, in 2019, was the guest editor of an issue of *Architectural Design* dedicated to this topic[96]. His work has ranged from digital discrete elements to, more recently, larger scale distinct physical components[78], and he connected computational design with digital assembly[102], in which customization occurs during assembly rather than in building blocks themselves. The key to effective fabrication lies in a design strategy in which discrete elements repeat and recombine and can be assembled into functional and complex buildings [78]. Gilles illustrated this approach in several design projects, the most iconic being the Tallinn Architecture Biennale Pavilion [78].

2.5.2 Robots, Robots, Robots!!!

They investigate their own solutions using rather small devices/robots that feel free to be used outside the laboratories and factories in the comfort of their homes or classrooms. The shift from the paradigm of the Industrial Revolution has turned towards custom made solutions. Such systems adapt to existing spaces, where they perform. Fabrication and use do not have to be separated, but solutions which can be applied in various environments emerge. The fabrication by small scale robots is typically more safe than larger robots for users and they are adaptive and can operate within larger spaces. In 2018, Maria Yablonia and Achim Menges introduced a catalogue of task specific mobile species [103].]. In their case, they worked with filament winding and depositing with fibre reinforced composites [91].

In their work, the developments of the 20th and 21st centuries noted above are reflected. New materials, digital tools, software, and accessibility of knowledge pushed architects to make their own designs by custom made devices/robots. The custom-made robots/devices are no longer limiting architects in their visions, but rather can express them exactly. The main thread of investigation lies in the technical development of such devices/robots and their simulation. This has shifted the emphasis away from the final design of a building/product. The development of distributed robots The development of distributed robots, including mobile assemblers and builders, is highly relevant to this dissertation. Notable investigations in this area are listed in Chapter 4.

2.5.3 Theodore Spyropoulos: Behaviour Complexity

The work of Spyropoulos goes beyond the investigation of distributed small-scale robots. These are no longer understand as a tool for fabrication of architecture. *They are architecture.*

Spyropoulos has investigated movement from known models towards adaptive ecologies that are active agents for communication and exploration, in which participation happens in real time and is active. Such architectures can sense, learn, and stimulate[1]. “thegoal is to construct a behaviour synthesis where complexity resides in the relationships between things, rather than as attributes to things” [2, p.41].

In 2017, Spyropoulos’ Hypercell project triggered broad interest in self-assembly and self-reconfigurable systems in architecture. Researchers and students in his team were able to develop a semi-functional prototype of adaptive ecologies. The system consisted of several modules with the ability to climb upon each other and to reconfigure the entire structure. Several years later, the lab continued this work by developing Hypercell [5] (the first self-reconfigurable functional system which focused on architecture) followed by Hexy, in which rigid mechanical parts were replaced by soft materials [104].

2.6 What is Next?

From the first standardization of architectural elements to self-reconfigurable adaptive ecologies, architects have witnessed dramatic changes in society, politics, technology, and ecology over the past two centuries. Today, architecture is reacting much faster than in the past on new inputs from industry than ever before. (Fig. 4) Architecture is reaching the point at which all the exciting developments over the past years will be able to be transferred to the creation of real, functional buildings—not just pavilions or interactive installations. Over the last three decades, architects have tested the boundaries of computer aided design and manufacturing (CAD/CAM). Now the challenge is to turn these tests into feasible and sustainable solutions accessible to everyone; if this turn does not happen, three decades of research will have been in vain. As seen in this section, such turning points are possible. The introduction of assembly lines and standardization significantly reduced the cost of produced cars in Henry Ford's factories. In architecture after 1945, standardization efforts resulted in standardized prefabricated housing estates. The more recent introduction of digital tools rapidly expanded architectural imagination, bringing with it new ideas and methodologies. By harnessing the computational power of current software tools, uncountable virtual variations of architectural designs can be generated and simulated. Autonomous assembly and on-site fabrication is also possible.

But what counts now is the creation of *real* buildings using new technologies. Throughout history, crises often lead to technology revolutions and architects have the expertise to choose the right way forward. Currently, architecture is tested in relation to a global pandemic. This will lead to questions regarding our technological environments [10]. Will we actually need physical buildings, or we can just work virtually? Will we turn our backs on an "artisan style" of work, or we will develop highly automatized digital societies? Can production continue without people by using robots? Or will nothing change? To the author of this dissertation, the question of what to do with architecture is pressing. Will we destroy old buildings that need to be serviced and maintained by humans, or we will adapt them to become intelligent autonomous environments which behave, heal, and adapt? How we will build new buildings, with or without people? Carpo recently reacted to the pandemic situation in his text "The Pandemic Changed Everything—or So We Thought" [105]. He found that the entire mechanical world (including factories and airports) melted down during virus lock downs, but digital economies and crafts remained. Artisans, including farmers and bakers, kept their business running, as did professions based on communications and working with data. Essentially, activities dating back to before the mechanical age helped keep humanity going during the crisis. This presents an interesting message for the future of architecture. Since discrete building blocks can be considered to be a physical representation of data (voxels) [78], voxel-based materials can "self-form" without the need for mechanized factories. If materials become as flexible and adaptive as data, architecture will no longer be dependent on industrial arms and factory production. The challenge is: how much we can transform buildings composed of mainly continuous analogue building elements into discretized functional buildings? In this case, "functional" would imply complex coordination of all building elements. In 2014, Rem Koolhaas deconstructed architecture into individual elements (e.g., knocks, doors, escalators, ceilings, and piping) as demonstrated in the "Elements" exhibition at the Venice Biennale[106]. This resulted in a complex encyclopaedia of thousands of building elements [107]. To develop fully automatized, autonomous, and discrete (modular) buildings, we must consider all such parts, not just walls.

2.7 Summary

The architectural roots of self-reconfigurable building systems are the result of certain developments since the dawn of the Information Age. Four primary direct influences have been highlighted in this dissertation: (1.) the limitations of automated construction created by industrial arms, (2.) the introduction of self-organizing models into architecture (e.g., cellular automata, swarm intelligence), (3.) discrete architecture, and (4.) reconfigurable/adaptive architecture.

Industrial Arms

After the introduction of popular industrial arms into architecture, the question of how arms can operate in spaces out of their reach arose. Small-scale cooperating robots—either self-organizing or self-reconfiguring— have been found to be one of the options for overcoming this limitation.

Self-organizing Models

After computational models based on swarm intelligence or cellular automata were introduced to architects, they were used as design tools (as seen in this author's previous work) in which agents track (Fig.6), or in which automata stages are generated towards, a certain stage in which they are frozen. Essentially, highly dynamic simulation has been used to achieve a non-dynamic static result. Later, architects did not continue down this path, which triggered the use of self-organizing models for controlling small-scale cooperating robots moving with building modular blocks or continuous morphologies such as fibres and 3D printers.

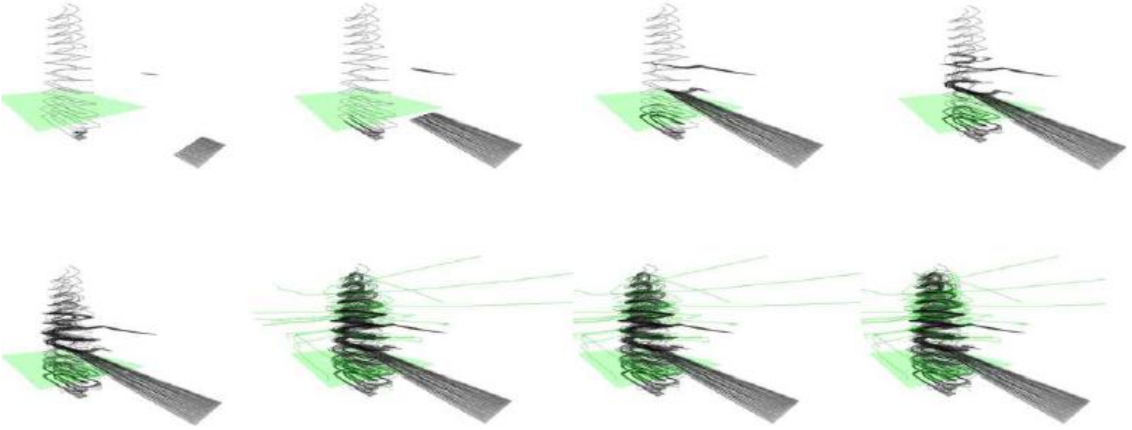


Fig. 6. Diagram showing the factors that have influenced self-reconfigurable modular building systems in architecture.

Reconfigurable/adaptive Architecture

Many interactive installations or active façade systems that have been built have captured the attention of architects. Architects have become fascinated with the idea that buildings can be dynamic when kinetic mechanisms are adapted to certain needs (e.g., weather, behaviours of inhabitants). While this was mostly about moving surfaces in the past, architecture has now embraced the idea that the whole building can be considered to be adaptive reconfigurable machines or organisms.

Discrete Architecture

The last factor of influence is the discretization of architecture into smaller parts, with attention turned to the question of why these parts should not be assembled autonomously through a bottom-up approach.

The cognitive map below, (Fig.7) describes the processes that have led to self-reconfigurable systems throughout architectural history. The map includes technological influences (right) discussed in the following sections on collective behaviour and distributed robots. Such technological influences determine the possibilities for technical solutions (e.g., self-reconfigurable modular robots or self-assembly).

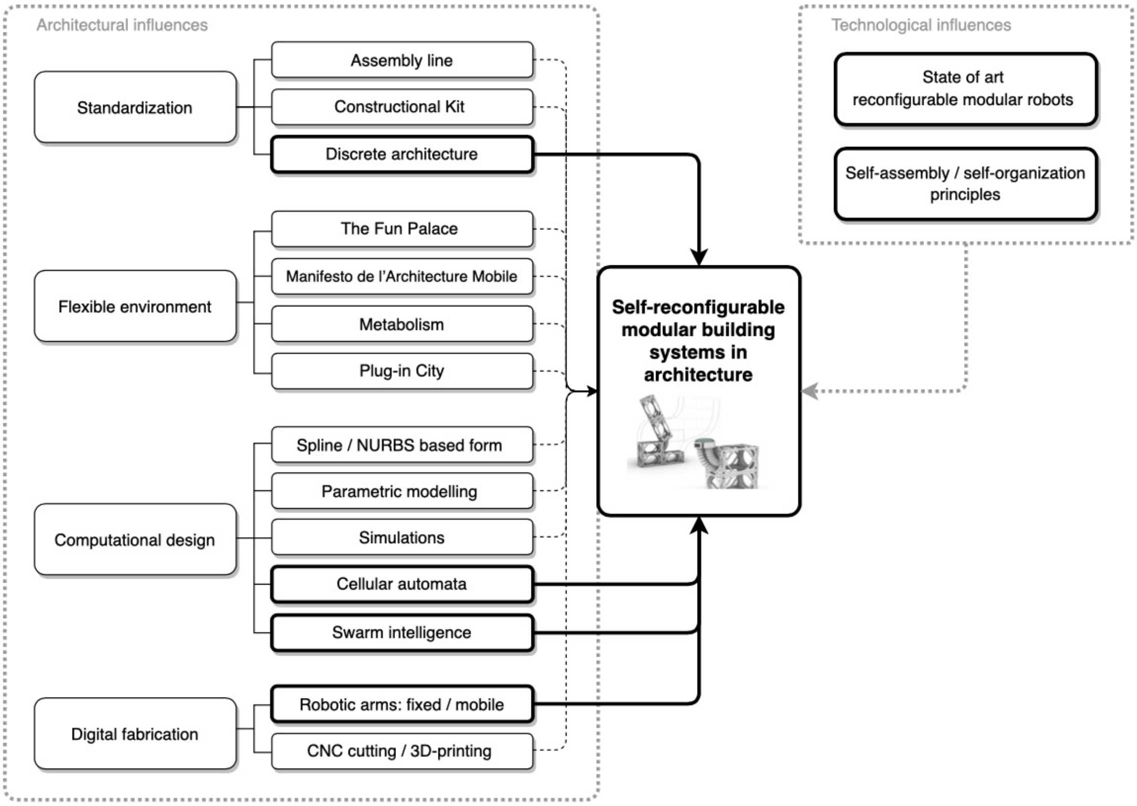
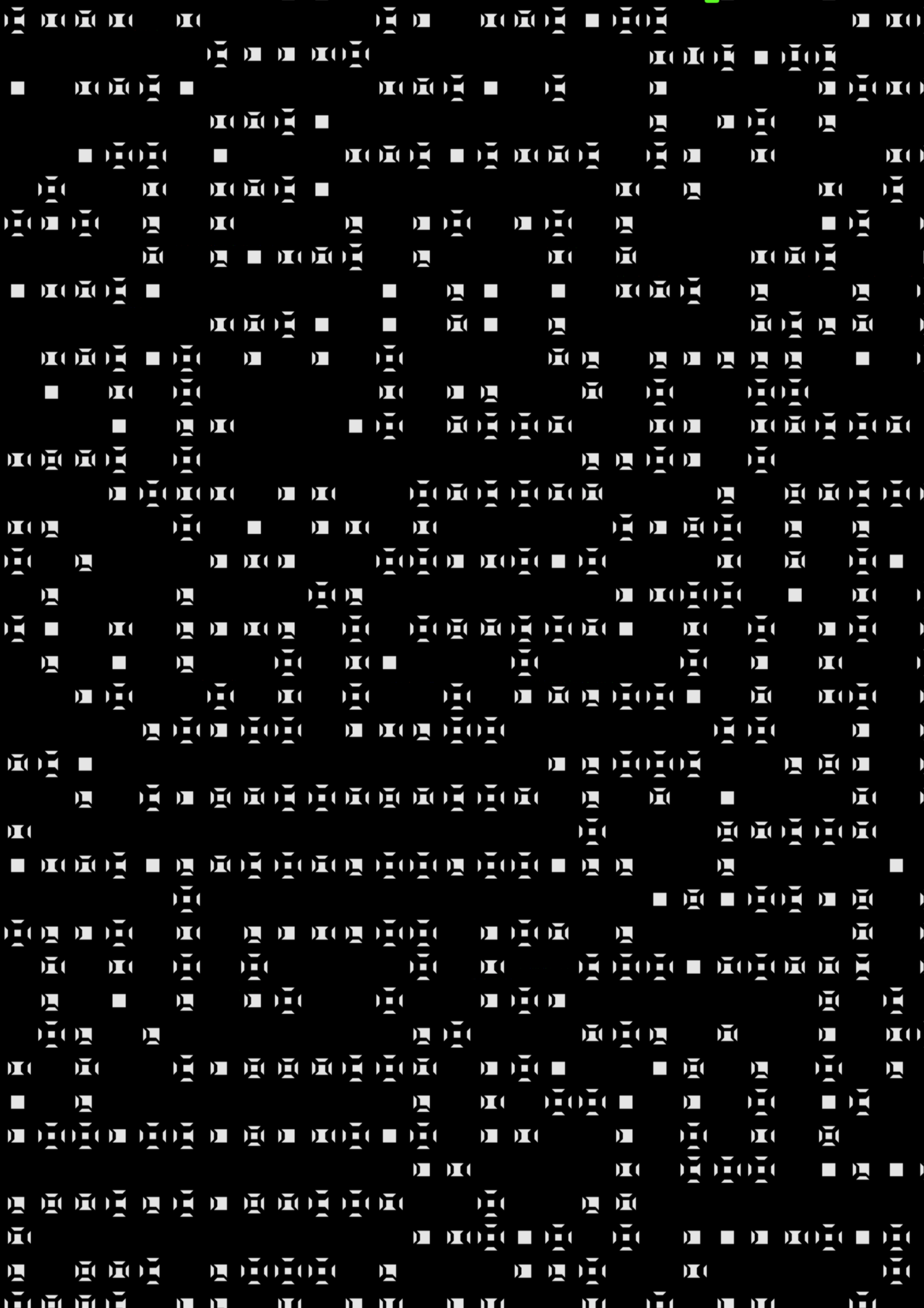


Fig. 7. Diagram showing the factors that have influenced self-reconfigurable modular building systems in architecture.



Chapter 3.

EMERGENT SYSTEMS AS A BASE FOR RECONFIGURABLE ARCHITECTURE

The increasing interest in automatization soon after the new millennium introduced a new labour force to architecture in the form of industrial robotic arms. Several research groups, including Gramazio & Kohler Research at ETH Zurich and ICD/ITKE at the University of Stuttgart, have built different research pavilions and experimental building elements to demonstrate processes in which human labour is partly replaced by use of industrial arms. Almost immediately after the first tests of using industrial arms to automate construction, many problems became apparent to researchers, such as the limitations for their use within an operating space, the difficulties posed by the heavy weight of the arms, and logistics(transportation to building site, moving within building site, transportation of products fabricated off-site). Five solutions to the challenges faced in implementing robotic arms to automate construction have been proposed to date and, to the best of my knowledge, include:

- The addition of robotic linear tracks, gantry systems, or mobile robots that extend an operating space[108].
- The discretization of fabrication, in which task-specific "mobile builders" are developed to create specific building forms [90].
- The discretization of an entire architectural plan, in which task-specific mobile assemblers reconfigure a building[7].
- The discretization of an entire architectural plan, in which a building is conceived of as a re-configurable modular robotic system[5], [109].
- A combination of these solutions (1 to 4).

The limiting factors of automated construction have pushed architects interested in the topic to consider different fields of study in order to better understand how natural organisms like animals or plants function. Millions of years of evolution have led to a spectrum of outcomes where natural systems are self-assembling, self-organizing, and/or self-replicating without the need of any external builder or assembler. Many of these principles have been studied for a long time in different research fields. Take, for instance, molecular self-assembly in chemistry [110], the folding of proteins [111] in biology, or state-of-the art modular robots in robotics[112]. One commonality observed for emergent systems is "bottom-up" interaction between individual simple elements and their environment(s) towards complex systems[113]. Considered in a philosophical sense: the self-assembly/organisation/replications, are origins of life[114]. The architectural task is to feasibly scale up such predominantly natural principles for the building of structures.

This chapter describes the self-assembly, self-organization, and self-replication/reproduction as well as how these concepts are currently understood in different fields ranging from biology to chemistry to computer science. Part of this chapter is devoted to a discussion of how the concept of emergent systems can be applied to the field of self reconfigurable architectural systems. The examples highlighted in the following sections are fundamental to understanding the experimental perspectives upon which this dissertation is based.

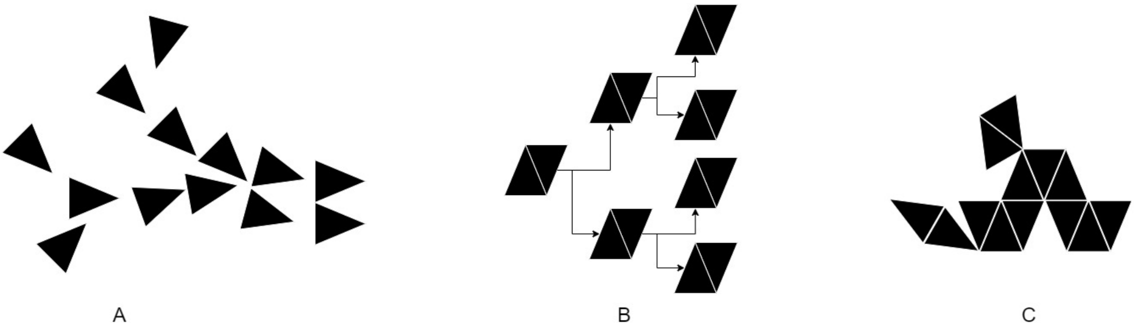


Fig. 8. Examples of emergent system types: (a) Self-organization, (b) Self-replication/reproduction, (c) Self-assembly.

3.1 Self-assembly

Self-assembly is a process in which disordered components are either connected or separated only by local interaction [16][111] in order to spontaneously build an ordered structure. Self-assembly is primarily investigated at the molecular scale (in the assembly of molecular crystals([111], for example) or, at the nanoscale, with the self-assembly of nanowires [111].. While the main research focus in self-assembly is on the molecular- or nanoscale, its principles can nevertheless be applied to the construction of macroscale architectural elements [6]. The key factor for applying self-assembly concepts to architecture and automated construction is ensuring precise interaction between building elements, through "bottom-up" assembly, Such elements can be relatively simple, but each of them plays a significant role in creating global forms. To select the optimal interaction from uncountable possible combinations is a challenge that nature has achieved through evolution, without deadlines and client expectations [115]. Researchers from different disciplines ranging from chemistry to biology, from nanotechnology to computer science, are trying to decode natural assembly mechanisms in order to have better control of interactions for applications in synthetic biology, in the creation of smart materials—and, more recently, architecture and automated construction[6]. The recent need to visualize self-assembly and to make prototypes of self-assembly robots, in particular, has spurred architects to be interested in self-assembly concepts[1], [5], [6], [8], [9], [104], [115].

The following sections provide an overview of recommendations for successfully applying self-assembly to architecture and automated construction. The recommendations are divided into four groups: (1.) assembly strategies, (2.) the design of individual elements, (3.) interaction and connection, and (4.) energy sources.

3.1.1 Architectural self-assembly recommendations

3.1.1.1 Assembly strategies

An “assembly strategy” defines an entire set of behaviours during the self-assembly process. Assembly strategies should be as simple as possible. The complexity/versatility of self-assembly increases exponentially with the number of elements (modules), which can lead to extremely expensive computations(Table 1.).

For self-assembly, form should follow sequencing, and should rather be the result of a generative process than try to fill predefined space exactly by assembling elements (modules) which may not fit in perfectly.

In reconfigurable architecture from discrete elements or physical voxels, weight must be considered. The author of this dissertation has learned from the production of prototypes that correct sequencing is crucial in order to avoid collisions between blocks and to eliminate the possibility of collapse during the assembly process.

	Number of possible directions of one joint			
	2	3	4	5
Number of modules	Number of configurations(self-intersection not considered)			
2	2	3	4	5
3	4	9	16	25
4	8	27	64	125
5	16	81	256	625
6	32	243	1024	3125
7	64	729	4096	15625
8	128	2187	16384	78125
9	256	6561	65536	390625
10	512	19683	262144	1953125
100	6.33825E+29	1.71793E+47	4.01735E+59	1.57772E+69

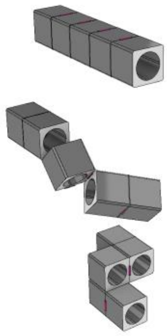


Table 1. Exponential growth of configuration of a simple chain provides up to five module joint directions (Up, Forward, Down, Left, and Right).

3.1.1.2 *Design of individual blocks*

The design of individual blocks is crucial for the design of an entire self-assembly system [116]. The geometry of individual elements (modules), as noted above, can be defined by an assembly strategy or, alternatively, geometry sets out a strategy. A module should be designed hand in hand with its guiding matrix and application. Overdesigning a module can lead to high computational complexity, and a large number of electromechanical parts makes a module expensive and heavy [117].. The materials used in modules should be easily fabricated, lightweight, and cost-effective. Since the construction industry works with higher tolerances [118], delicate components with high-precision requirements should therefore be minimalized.

3.1.1.3 *Interaction and connection*

The position of connecting mechanisms influences the overall behaviour of any self-assembly system and represents one of the most challenging parts of a system's design. Connections must enable both strong fixation in a static state as well as detachability during transformation. Both connecting mechanisms and connections must be simple, lightweight, and cost-efficient. In the author's experience, minimizing torque in connections as much as possible in system design is highly recommended [119]. If possible, connections should be genderless ("hermaphroditic") in order not to limit the range of possible configurations [112].

3.1.1.4 *Energy sources*

Before an energy source is selected, every automated construction project should be analysed according to energy interactions and energy performance. Modular self-assembly robots often carry their energy sources on board with them. This presents a "closed circle" problem: in order to move with neighbouring modules, energy is needed. More energy requires a bigger battery, which in turn is heavier, making the entire module heavier, in turn leading to higher energy requirements. To avoid this "closed circle" issue, the author recommends that energy sources be separate from assembled modules. Solution can be found in chain architecture [120] (described in section 4.1.1) where energy source can be fixed at one of the end of the chain (typically on the ground). In which an energy source can be fixed at one of the end of the chain (typically on the ground). In such systems, all necessary cables should be positioned inside the chain. To minimize environmental impact, renewable energy sources are recommended for all the types of reconfigurable systems.

3.1.2 Self-assembly at the molecular scale

Self-assembly has been heavily investigated at the molecular scale in the field of molecular biology in order to, for example, guide disordered molecules into complex nanostructures or macrostructures [111]. A molecule, consisting of more than one atom held together by a chemical bond, either covalent or ionic [121], is the basic building block of the organized structure of an organic substance. Molecules can be homonuclear, consisting of atoms of one chemical element such as oxygen (O_2),. or they can be "heteronuclear" and be composed of different chemical elements (e.g., water, H_2O) [122]. The properties of individual molecules defined by the composition of their atoms define the features of final substances and also includes attraction and repulsion between molecules determined by their electromagnetic properties [123]. The complementary shape of molecules is used in a process called "docking" that keeps molecules fixed together and defines their orientation, similar to a jigsaw puzzle [123].

Molecular assembly is much more complex than can be described in the context of this dissertation. The features listed above offer only a necessary understanding of how substances are formed at the molecular scale in order to shed light on concepts which can be used in macroscale assembly for architectural and construction purposes. Molecular self-assembly is affected by highly precise sequences and the orientation of individual molecules. The most relevant and inspiring processes of molecular self-assembly which the author of this dissertation sees as relevant for understanding at the macroscale include: self-assembled monolayers, folding proteins, DNA, and crystallization of polymers.

3.1.2.1 Self-assembled monolayers

Self-assembled monolayers (SAMs) are molecular structures spontaneously formed by precisely ordered molecular chains formed on a surface with convenient substrates [124][125]. A molecular chain consists of a head group and a tail group of molecules. The function of a head group is to interact with a surface through chemisorption; disordered head groups form into two-dimensional structures [124]. A tail group provides a specific function in the molecular chain and forms groups into three-dimensional molecular structures by way of intermolecular interactions. Most SAMs studied are metal substrates, especially gold [125], and are used primarily as surface protection layers or as thin layer films with different functions like chemical resistance, humidity protection, conductivity modification, or hydrophobicity [126]. Different studies have been conducted for use in biosensors [127] and superlattices [128].

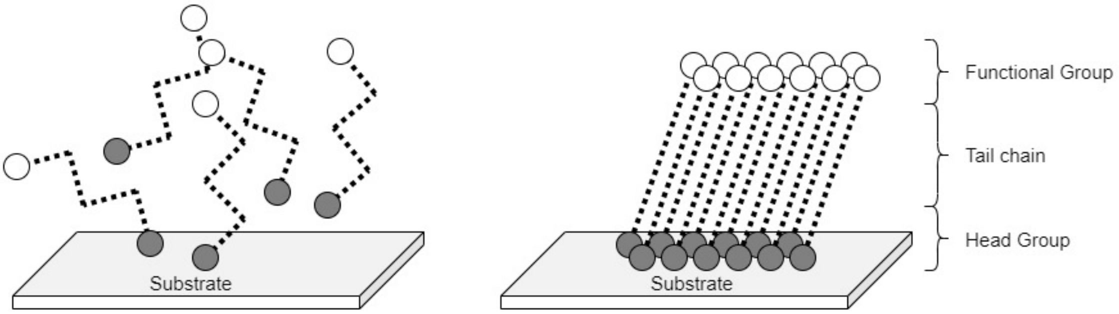


Fig. 9. Assembly process of self-assembled monolayers .

The process of forming self-assembled monolayers has potentially useful macroscale architectural applications. The author of this dissertation has investigated the idea of a façade material in which thousands of tiny “hairs” reconfigure on a building’s exterior layer (Fig. 10). Reconfiguration would be facilitated by the attraction and repulsion at the tip of the hairs performing under different weathering conditions. The advantage of such a system would be the range of potential applications for covering different types of skin geometries, from conventional verticals geometries to highly organic designs. Another potential application include an interactive multimedia façade [129], in which traditional display pixels would be replaced by thousands of assembling hairs. Self-assembled monolayers also have the potential for use in architectural surface applications, in which classical matrix-based façade and cladding systems could be supplied by self-assembled hairs, chains, strings, and so on, thus facilitating multiple functions.

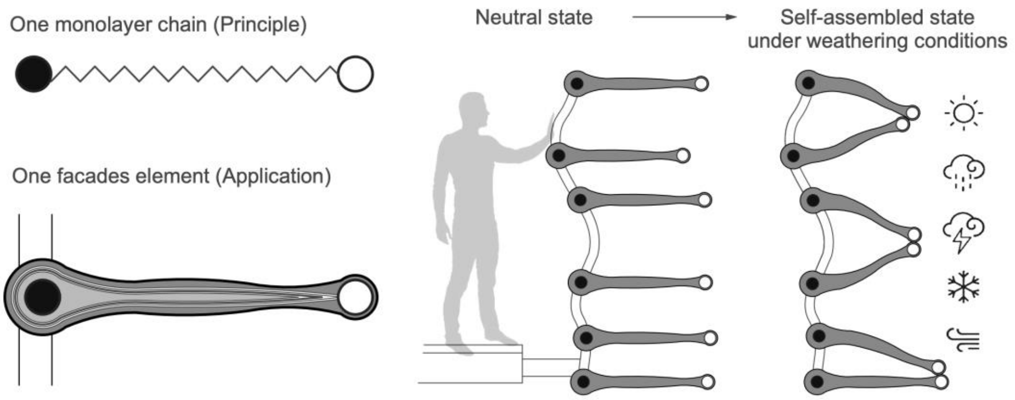


Fig. 10. Concept of self-assembled monolayers transformed into façade system.

3.1.2.2 Folding proteins

Proteins are a class of chemicals responsible for many functions in our bodies such as walking, thinking, and digesting. Proteins are condensation polymers forming peptide linkages of amino acids between a carboxylic acid functional group of one molecule and an amino functional group of another molecule to make one dimensional chains, splitting out water, as the process continues to unfolded chains or random coils (so-called nascent proteins, which are non-functional). Hydrogen bonding between individual amino acids enables proteins fold into three-dimensional shapes called native proteins. The native form is essential for protein function [130].

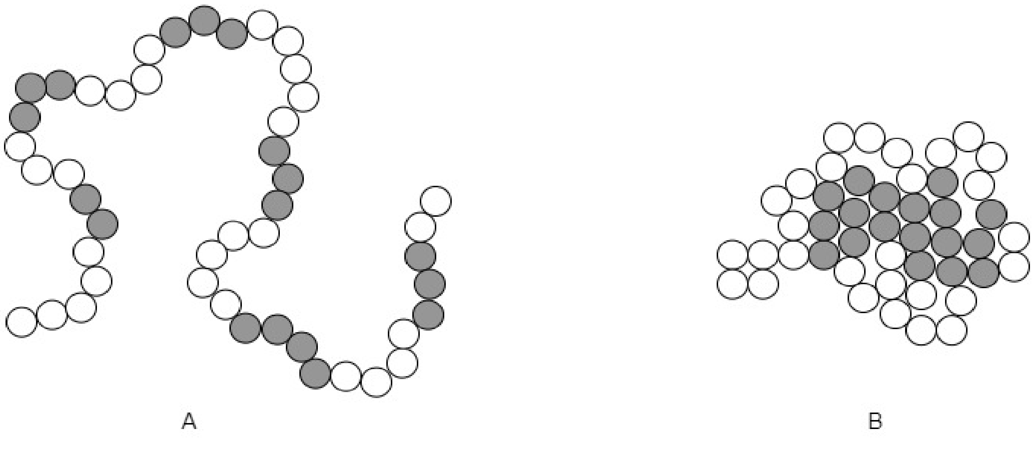


Fig. 11. Folding of proteins with hydrophobic effect: (A.) Unfolded protein, (B.) Folded protein: hydrophobic amino acids tend to accumulate in the centre of a structure. Based on [131].

Proteins consist of a different number of amino acid types; their sequence defines the folding process and final shape. Proteins have a different level of complexity while simple domain proteins can fold extremely fast in one step [132]. The folding process of multidomain proteins can take hours and must pass through several intermediate steps before it folds into its final shape. Because protein folding is a complex process, “misfolding” also happens. Specifically, when a native three-dimensional structure contains extracellular or intracellular dysfunctional aggregates, this can lead to problems such as Alzheimer’s or Parkinson’s diseases or to various allergies [133]. Decoding of the folding process is one of the most challenging tasks in chemistry which might lead to the curing of several diseases, improvement of drug delivery mechanisms, or even be an inspiration for large scales mechanisms that can work like billions of protein machines (pumps, motors, and so on) located inside of our body [134]. Computer dynamic simulation, particular of multidomain proteins, is extremely complex. Almost an endless number of protein configurations must be evaluated before a final one is found, and often supercomputers are unable to calculate this efficiently. Several prediction techniques have been developed which can be divided into three main groups: comparative modelling [135], fold recognition [136], and the ab-initio method [137].

- *Comparative modelling* compares an unknown protein sequence with structurally known proteins or assembly parts [135].
- *Fold recognition* predicts an unknown structure with already existing folds [136].
- The *Ab-initio method* is used when a similar database of sequences, structures, or folds does not exist; with it, a solution with the lowest energy consumption is sought [137].

Many software tools have been developed for self-assembly prediction using different computing methods, including machine learning and deep learning [138]. The most popular prediction software tools at the time of writing this dissertation include *Modeller* [139], *FoldX* [140], *I-TASSER,* [141], *and Rosetta* [142].

The extreme complexity of simulations and predictions has triggered methods including human decision making as a part of the interactive process, programmed as games in which players try to find a native form of protein. The most famous of these is *Fold-it,* developed in 2008 by Baker, Popovic, and Salesin after they figured out that humans are very efficient in the fold-finding process [143][144][145]. The game uses distributed computing, where players share their ideas and experiences in forums to solve certain proteins and get the highest score. Players, together with researchers, have solved the Crystal structure of a monomeric retroviral protease [144] and have contributed significantly to Diels-Alder reactions [145]. At the time of writing this dissertation (2020), players are designing an antiviral protein to combat the coronavirus [143].

The power of distributed computing has been also used in a project called *Folding@home*. Users share the CPU time of their personal computers for more rapid running of protein simulations and predictions. *Folding@home* was established in 2000 at the Pande Laboratory at Stanford University and has gained high popularity recently with the coronavirus pandemic [146][147].

Researchers investigating folding of proteins often work with a library of already known movements/reconfigurations which they combine in a final assembly. For the building industry, the discretization of movements is necessary for the implementation of self-assembly in architecture. The author suggests the future creation of a library of discrete movements that are already optimized and calculated for architectural purposes. Later, these could be combined with sequences for global assembly. The concept of discrete movements would effectively fulfil all requirements while reducing computational time and providing higher overall control. (Fig. 12). The integration of “users” into the design process, who could play with houses, apartments, offices, and so on. like in computer games, is also an interesting concept and could have a positive effect on homeowners by making them feel empowered in the design process.

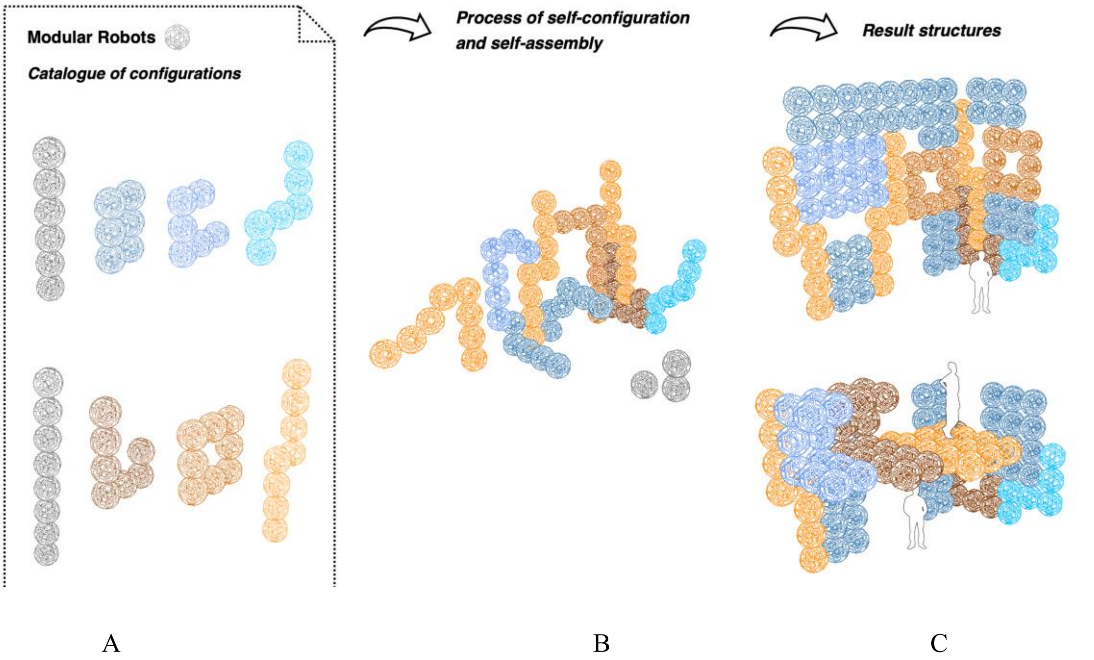


Fig. 12. Proposed idea of discretization of folding steps and their combination towards higher level of assembly complexity by reconfigurable robots. (A.) Catalogue of configuration with already solved forming (blue = six module chain, Orange = eight module chain) ,(B.) Process of self-configuration and self -assembly combining already known assemblies, (C.) Final structure as combination of discrete configurations.

3.1.2.3 Lattice proteins

Lattice proteins are simplified models for folding proteins that follow a regular matrix in order to achieve a reduction in computational time. This section is devoted to them because the lattice geometrical form of an assembly has closer ties to architectural applications than the other models of folding proteins mentioned in the previous section. Lattice protein models usually consist of a single chain of vertices and edges formed into a self-avoiding path on 2D and 3D regular lattices(Fig. 13).

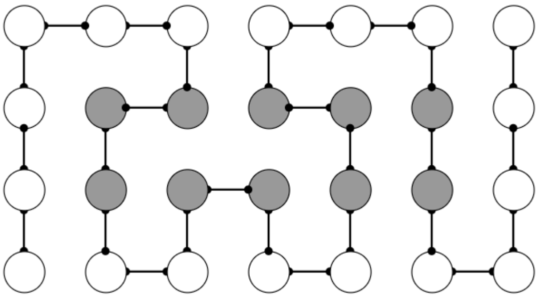


Fig. 13. Lattice protein

The *Hydrophobic-polar model* is the most popular lattice protein method. The model is simplified to include only two amino-acid types: hydrophobic and polar, since most proteins only use these two, with hydrophobic amino acids situated in the core of a native protein and with polar acids on the surface, in contact with a polar environment [148].

Dil [149] introduced the first *Hydrophobic-polar* model in 1985. Several approximations of the original *Hydrophobic-polar model* have followed such as the implementation of side chains [150] or the use of hexagonal or triangular matrices [151] as well as Monte Carlo methods [152] and Ant colony optimization [153].

3.1.2.4 Deoxyribonucleic acid (DNA)

DNA is a molecule formed by two helical polynucleotide chains of atoms twisted around a common axis connected by hydrogen bonds [154][155][156]. DNA carries genetic information that defines the formation of proteins in living organisms and is important, among other things, for "correct" reproduction, the analysis of genetic diseases, and genetic engineering [156].

Regarding the link to this dissertation, the assembly of DNA structures and their possible scale-up methods is interesting from the architectural/self-assembly perspective, particularly the programmable assembly of DNA Origami, DNA Bricks, and DNA machines.

3.1.2.4.1 DNA origami

Since 2006, when Rothemund introduced the idea of DNA origami [157], the concept has been broadly investigated by scientists, including various nanoscale applications such as drug delivery, plasmonic circuits, molecular robots, and electronics [157]. A "bottom-up" self-assembly approach refers to short DNA molecular strands being assembled into a single long strand formed into a target 2D or 3D nanostructure [157]. The structures can, for instance, even include active hinges, as was demonstrated on a DNA box which had a controllable lid [158] and an assembly into a tensegrity structure [159]. The assembly logic of DNA origami can be a simple scale-up in which individual short strands represent the macroscale building blocks used in architectural self-assembly. To find the correct sequencing and folding patterns of DNA long strands, different open source software tools have been developed including SARSE [160], caDNAno [161], canDo [162], and FracTileCompiler [163]. They are also very useful for architects, who can abstract the geometry of DNA structures through them into the geometry of a desired building.

3.1.2.4.2 DNA brick self-assembly

Researchers at the Wyss Institute for Biologically Inspired Engineering at Harvard University originally developed DNA brick self-assembly, which functions in a manner similar to Lego® bricks. A DNA brick is formed by a single synthetic DNA strand into a complementary shape and each brick has the only one unique sequence of DNA, allowing it to fit into one location within a whole desired discrete shape by DNA base pairing[164]. Hundreds of different shapes 25 nanometres in size have been developed which consist of bricks (voxels) 2.5 nanometres at each edge [165].

3.1.2.4.3 DNA machines

Similar to an automotive factory, where different machines manufacture the final car, molecular machines can also assemble different molecules into desired nanostructures. The idea of DNA machines was introduced already in the late 1980s by Seeman[166], and since then, the manufacture of tweezers, cranes, walkers, springs, gears, sorting robots, and other devices using DNA machine concepts has been investigated [167]. DNA molecules have been found to be ideal for creating molecular devices because of their programmable kinetic, thermodynamic, and assembly properties [168]. DNA machines mimic large scale machines in which, for example, nucleic acid strands, light, pH, and metal ions trigger movements [167]. The "solid" parts of molecular machines usually incorporate the principles of DNA origami. In 2017, researchers from the California Institute of Technology developed a cargo sorting DNA robot which can walk on a DNA origami surface as well as pick and place two types of molecules [168].

The recent developments in the areas of DNA machines and DNA bricks reflect a fractal-based logic of assembly: DNA is first composed into elements and then final structures are assembled later. These elements can even enable movement, as seen in DNA machines [167]. DNA machine methods can inspire architects to think about architectural assembly in a similar way: first, machines are self-assembled from individual blocks; later, a desired structure is completed from the rest of the blocks similar to the way cranes and robots assemble components on a building site.

3.1.2.5 Crystallization of polymers

The crystallization process of polymers is relevant to the concepts underpinning this dissertation because through this process, polymer molecular chains form into regular or semi-regular structures [1]—likewise, one can imagine self-assembly techniques for architecture in which building blocks "form" into regular/semi-regular structures. Turning back to polymers: the main interest for the purposes of this dissertation lies in a basic understanding of semi-crystalline and mainly crystalline polymers. It is important to stress out that no polymer can be crystallized 100%.

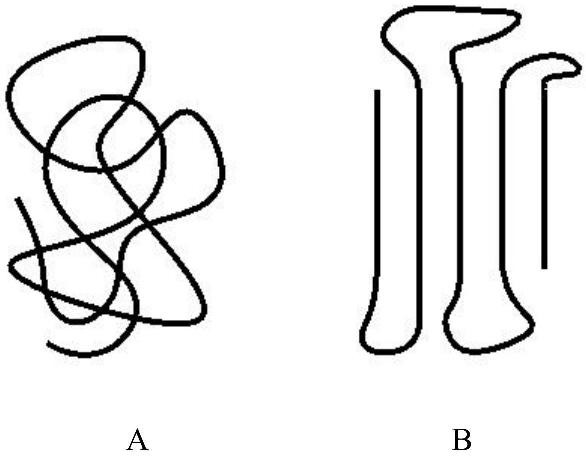


Fig. 14. Polymer arrangement: (A.) Amorphous, (B.) Semicrystalline

Most polymers are semi-crystalline, meaning they combine crystalline areas and amorphous areas. The ratio between crystalline areas and amorphous areas defines the degree of crystallinity, important for the selection of polymers for end use. Polymers such as polyethylene (PE) or polypropylene (PP) have the ability to be formed into desired shapes with minimum amorphous areas. Their crystalline areas are highly ordered into parallel rows of molecules, similar to bricks in a wall. The crystallization of polymers shows how stable shapes can be formed, even if they include non-stable amorphous areas with random orientations. In considering this, architects should feel free to consider self-assembly structures that are not always perfect and precise according to their desired shapes. The strongest polymers reach a degree of crystallinity of approximately 80%. This shows that the 20% is allocated for amorphous areas.

---

[1] Not all polymers assemble into regular structures. Amorphous polymers such as Poly(methyl methacrylate) (PMMA) and Polyvinylchloride (PVC) are formed into structures with random orientation of chains [291] and will be not discussed further, being out of scope for this dissertation.

Although it seems that amorphous areas do not have any function, they account for most of the elastic and inelastic deformations in a structure. Imagine an architectural structure where, from one chain material, it would be possible to achieve both elastic and rigid areas.

3.1.2.6 Summary: molecular self-assembly towards architecture

This section of the dissertation explored the self-assembly (SA) of different structures and materials in different fields as well as their possible application to architecture. The examples selected showed possible new paths for architectural self-assembly inspired by scientific principles of molecular self-assembly.

In the biological world, assembly usually does not take place only from one chain, as illustrated in the folding of proteins, DNA, and even the crystallization of polymers. Individual chains are often interlocked with one other into final structures through complementary shapes of folded cluster and chemical bonds. The chemical bonds are, at a larger scale, negligible and interlocking stability and strength should be sufficiently provided by complementary geometries [110]. The replacement of a single chain by several smaller chains enables higher manipulation freedom in which the reconfiguration of individual areas does not require moving the rest of the chains. Thus, these can stay in position within a structure. Discretisation into smaller chains reduce the torque in joints and hinges. This is in particular important at larger scales in which a chain is not supported by any substance[132]. On the other hand, the subdivision of chains can break the continuity of an entire structure. This could be problematic if continuous infrastructures such as tubing, cables, and so on are used in an architectural design.

Because of their higher complexity, chain structures usually do not exactly form into the desired shapes as do folding proteins and crystallization of polymers. In proteins, incorrectly folded areas cause several diseases in polymer chains that form into areas with elastic deformation. The folding of chains in nature is mostly not perfect; rather, it represents an optimal balance in between evolution time, folding time, or the number of molecules. The ratio between correctly and incorrectly packed areas should also be considered in future architectural implementations because they are a natural negative side effect of the highly effective and complex process of folding.

The dense packing and shape filling [169] of a desired object is the most important aspect for final fixed architectural structures—and especially the crucial building sequence. Unfinished areas should be temporarily supported, and live and dynamic loads must be calculated for every assembly step. These are just a few main examples of the great complexity of a self-assembly process.

Self-assembly in architecture is still relatively a new topic. On the other hand, in chemistry and molecular biology, self-assembly has been studied for many decades and new software tools, techniques, and methods were developed as these investigations progressed. Architects do not have to start from scratch if they wish to catch up in their understanding of self-assembly and its applications, but they can modify and scale up already investigated self-assembly techniques, tools, and concepts.

3.1.3 Self-assembly at the macroscale

This section describes recent developments in self-assembly at the macroscopic scale. The macroscopic scale is defined as being “the size of an object visible to the naked eye.” Even some of the molecular self-assembly mechanisms such as self-assembled monolayers and polymer crystallization can develop into macroscale formations. This section is focused instead on macroscale objects which either mimic molecular self-assembly or have their own logic mechanisms. Even though self-reconfigurable modular robots can be used in macroscale self-assembly and are essential for this dissertation, they will not be discussed in this chapter. Rather, Section 4.1 is devoted to the detailed description and comparison of several selected modular reconfigurable robots.

3.1.3.1 Works of the Self-assembly lab

Works created at the Self-Assembly Lab at the Department of Architecture at the Massachusetts Institute of Technology (U.S.) led by Tibbits stand at the cutting edge of the macroscopic use of self-assembly for architectural and design applications [170]. Research is focused on converting collective bottom-up processes such as self-assembly, self-organization, self-replication, adaptation, and repair into real-world construction and manufacture. Combining research and physical prototyping, students and researchers have produced macroscale objects, mainly for use in design and architecture. The lab’s goal is to avoid or minimize the use of electronics such as sensors or actuators as well as mechanical parts (gearboxes, bearings, and so on) and rather aims to provide necessary movement by employing smart responsive materials. Tibbits, in *Self-Assembly Lab:*

Experiments in Programming Matter [16], has provided the following characteristics of self-assembly for use in construction and manufacturing processes:

1. *New solutions can spontaneously emerge that may not have been foreseen previously,*
2. *New materials and behaviours can be created that are outside the limits of human or machine control.*
3. *Structures or products can be highly adaptive.*
4. *More robust systems can be created due to the redundancy and error-correction.*
5. *Efficiency can be gained in manufacturing processes with parallelization or even exponential production, rather than linear sequences.*
6. *Alternative forms of energies can be used.*

From all the lab projects [16], the following two have been selected to highlight in this dissertation because of their applicability to architectural implementations, uniqueness, and diversity in terms of providing creative solutions.

3.1.3.1.1 4D printing

Fabrication technique when 3D printed objects self-form into a desired shape[171]. Such objects do not contain any electro-mechanical parts and all movement is achieved by use of material properties. 4D printed objects are produced as 1D strands or 2D surfaces with predefined hinge zones which can transform themselves into 3D objects. Two polymers, each with different expansions or contractions, are used. Movement is provided mainly through a hydrogel which swells up to 150% when submerged in water [16]. 4D printing provides an excellent example of how self-assembly can be achieved solely by means of a smart material solution without the use of sophisticated mechatronic heavy tools. On the other hand, it is unclear at the time of writing of this dissertation how this technique could be scaled up to an architectural scale without the use of surrounding water.

3.1.3.1.2 Aerial assemblies

Several modules consisting of helium balloon (91cm) surrounded by truncated octahedron composite frames autonomously compose in the air to form larger compositions (lattices, beams, or cubes). Final conglomeration is achieved through positive and negative Velcro nodes having specific patterns [16]. Modules randomly move inside a university yard defining the environment boundaries until the right compositions are achieved. Aerial assemblies illustrate how even large-scale modules can self-assemble into desired forms without the use of sophisticated mechatronic parts. Similar to other projects from the lab such as *Fluid crystallization* and *Self-assembly line* [16].

3.1.3.2 Self-assembly of microelectronics

According to research conducted by the author to date, it appears the “grand challenge” in architectural self-assembly is scaling it up. Inspirational processes can be found in microelectronics, where the focus is on scaling them down. Standard “pick and place” assemblies limit the size of chips, diodes, conductors, and so on. Even though they can be manufactured at smaller sizes, size limitations are based on the effective assembly and precise alignment of manipulating devices. The process is driven by molten solder bumps that reduce surface free energy when microelectronics are transported in a liquid into the desired pattern [172]. Most self-assembly takes place on 2D surfaces, which can be rigid as well as flexible (highly interesting in terms of possible use in new flexible electronics technologies). In 2000, the Whitesides Research Group at Harvard University (U.S.) published an article describing a 3D electrical network that had been self-assembled. The network consisted of discrete truncated octahedrons with faces covered by copper dots, wires, and LEDs. Polyhedrons were then coated by solder and self-assembly in an isodense, aqueous, hot KBr solution [173].

3.2 Self-Organization

The terms “self-organization” and “self-assembly” often overlap each other, and various scientific disciplines interpret them differently, making definitions even more confusing. For example, “dynamic self-assembly” corresponds to what biologists interpret as self-organisation [174]. To make it clear for the scope of this dissertation, the author follows the Tibbits definition, where the main difference is in the final state of self-organized/assembled configuration[170]. My definition is modified as follows:

> *Self-organization is a bottom-up process where individual agents move through their local interactions towards a final configuration, where each agent does not have one predefined position, but rather oscillates around several target positions.*

3.2.1 Principles of self-organization

In other words, self-organization is a bottom-up process in which individual components form a target configuration only by interacting with on another and their environments through simple rules. Self-organized systems are not centrally controlled from top to bottom, but rather are decentralized, without need for blueprints, directors, and the like [175]. With collective decision making, several solutions can be achieved through local interactions when a solution does not depend on the decision of an individual but rather on decisions that emerge solely from the interaction of system components [176].

Bonabeau et al. (1997) outlined four ingredients for self-organisation: positive feedback, negative feedback, amplification of fluctuations, and multiple interaction [177].

- *Positive feedback*: The result of an execution of simple behavioural rules that positively support the forming process of a structure [177]. This can be, for instance, a pheromone trail created by ants during their food searching which helps other members with orientation [178][179].
- *Negative feedback*: Counterbalances positive feedback, which stabilizes overall system behaviour [177]. This can be, for instance, depletion of a food source or evaporation of pheromone trail [179].
- *Amplification of fluctuations*: Random walks, wrong decisions, or random task switching help a system to discover new, unpredictable solutions crucial for the entire system [177]. For instance, in an ant colony, random movement forces the ants towards an initial food discovery. On the other hand, errors in the decisions of an individual ant can lead to the discovery of completely new sources of food, which would not happen by following the strongest pheromone trail correctly.
- *Multiple interaction*: By direct interaction with visual, physical, or chemical contacts, agents respond to actions. For instance, flocks of birds. In stigmergic interaction, agents respond indirectly by modifying an environment (e.g., ants following a pheromone trail or wasps building nests).

This section is divided into two parts *swarm intelligence*, and *cellular automata.* Multi-agent systems and other self-organisation systems found in the fields of chemistry or physics are beyond the scope of this dissertation.

3.2.2 Swarm Intelligence

Swarm intelligence is a decentralized self-organizing system which harnesses natural intelligence for artificial applications. It is represented in different natural models and predominantly mimics the behaviour of social insects. The term “swarm” was firstly introduced by Beni and Wang in 1989 [180] as a differentiation of cellular robotics already used by Fukuda [180], [181]. Swarm intelligence combines the research of biologists who analyse certain rules of behaviour in swarming natural systems with computer scientists, who transfer these rules into algorithms which are often used for the control of multiple robots. The word “swarm” covers different types of natural behaviours like flocking (birds) and schooling (fish) as well as human-animal interactions like hunting and herding. Behaviour is performed by individual members called “agents”. Agents interact through simple rules between an environment and other members. By cooperating, agents are able to achieve tasks which are too complicated for individuals such as protection from predators, energy saving, and searching for food.

Swarm intelligence has been used in logistics, animation, medicine, architecture, data mining, and other fields[182]. Some of the models have been adapted for simulating human social behaviour. Swarm intelligence gained the interest of researchers in different fields because of its robustness, simplicity, high adaptivity, decentralization, and ability to be computed cheaply. Several models are selected and briefly described below.

3.2.2.1 Ant colony optimization

The Ant Colony Optimization algorithm was first introduced by Dorigo in 1992 [183]. The algorithm took its inspiration from the stigmergic behaviour of ants while searching for food. The term “stigmergy” was coined by French entomologist Pierre-Paul Grasse, who described it as the condition when “workers are stimulated by the performance they have achieved” [184][185]. Stigmergy can be indirect when insects modify their environment or local when it can be only accessed by insects in a certain visited area where they were released [185]. Stigmergy can be observed in many ant species while searching for food. Initially, ants walk randomly from their food nest until they find a food source. While walking, they deposit a pheromone trail that works as positive feedback for other ants. When an ant finds a food source, it comes back to the nest following the path. Pheromone trails have specific odours that get weaker over time, which means shorter trails smell stronger. Ants are attracted by the trails with the strongest odours, and selected trails even smell even stronger because of constant deposition of pheromones by more ants. This helps to an ant colony find the optimal path from nest to food source. The Ant Colony Optimization algorithm has been used for the travelling salesperson problem, when the goal is to find the optimal shortest Hamiltonian path within all the analysed points [186]. Other applications lie in solving metaheuristic problems [185]. Ant colony optimization can be used in architectural design for shortest path simulation[187], space generative design[188], and the control of mobile robots moved within two dimensional regular grid [189].

3.2.2.2 Boids

One of the most popular swarming models was developed by Reynolds in the late 1980s to simulate complex movements such as flocking (birds), fish (schooling), and herding (land animals) [190]. Originally employed in computer graphics and for movies like *Tron* (1982) and *Batman Returns* (1992), it has also captured the interest of architects in terms of generative design, space optimization, and the control of robots. Boids balance between members' needs to be in a group and the maintenance of individual space that keeps a swarm in a significant, fascinating aggregation. As with other swarm models, there is no leader [182]. Movement and decision making are based on local interaction of individual agents (birds, fish) through three simple basic rules: separation, alignment, and cohesion.

- *Separation* refers to maintaining a certain distance between agents and avoiding their collisions.
- *Alignment* steers agents toward the front of a group.
- *Cohesion* forces agents into the centre of a group.

Simple rules are often extended to include obstacle avoidance and steering towards a target. Flock-like behaviours can be also used for simulating the movements of crowds of people[191] and further used for optimizing architectural spaces[191]. Due to well-developed simulations and software plugins such as Quelea (Grasshopper Plugin) and Plethora[192] are the most commonly used swarm system by architects (Fig 15).

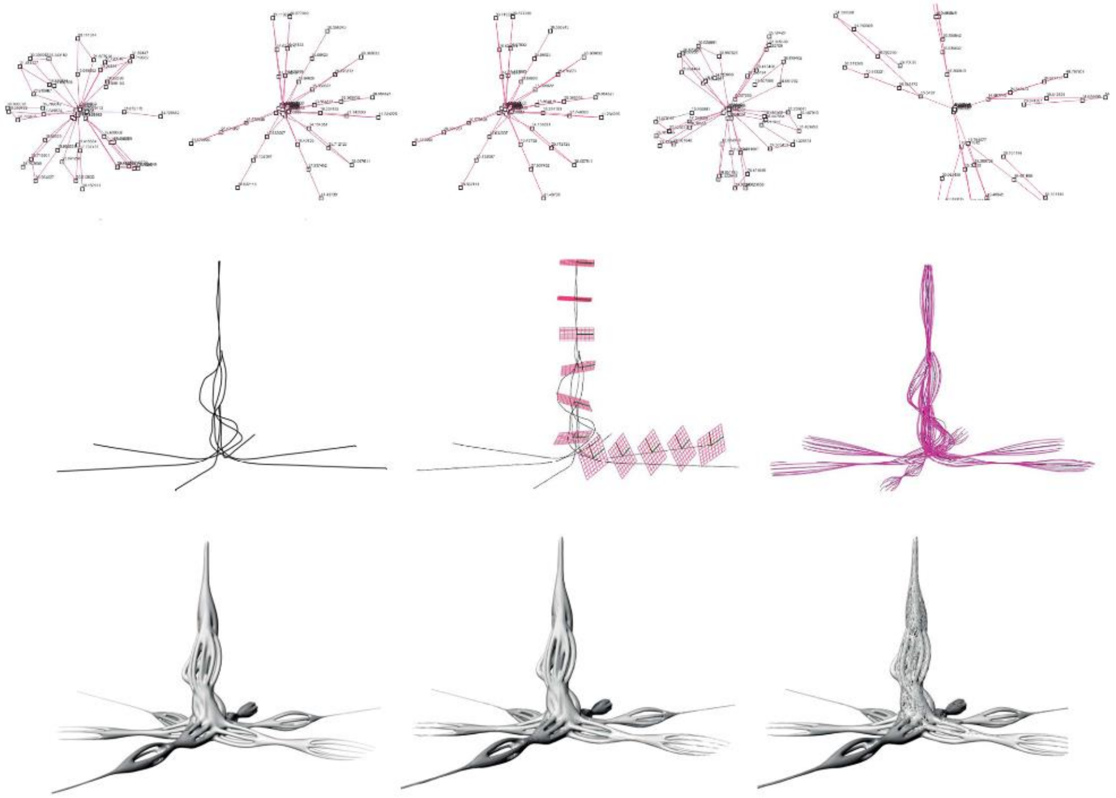


Fig. 15. Author of this thesis used boids as a design tool for the generation of a static building (Skyscraper) by leaving the track behind the agents following swarming rules.

3.2.2.3 Termites

Algorithms investigating the unique behaviours of termites are of interest for their indirect stigmergy. Termites create sophisticated mounds above their nests accompanied by natural ventilation systems. These biological towers are the result of the collective work of millions of tiny (1–2 mm long) and completely blind individuals [193]. Like bees, wasps, and ants, a termite colony has different castes responsible for certain tasks. There are approximately 2,400 species worldwide [194][195]. Regarding collective construction, the most interesting are Macrotermes [196][195], excellent self-organized architects. Macrotermes do everything without any central guidance. By instinct and cooperation, they drop grains of soil at the right places and build remarkably complex mounds. These mounds create the conditions for growing the fungi used in the feeding of their offspring. Mounds have conic shapes with inner ventilation ducts from the bottom to almost the top of a mound. Ducts provide proper ventilation conditions by opening and closing millimetre size pores on the outer surface of the mound for fungi grown in the central part, in special combs or galleries [197].

Termites have not been investigated as extensively as ants have been in computer science. However, the behaviour of termites has been used for the control of the significant self-organized construction robotic system, Termes [7], which is described in detail in Section 4.2.

3.2.2.4 Wasps

Social paper wasps have been investigated because of their bottom up building strategies employed while building nests. Like termites, they use stigmergy to orient themselves in a building sequence defined by the orientation of hexagonal cells. These cells are a mix of natural plant fibres and wood pulp chewed and cemented together into a resulting paper material [193]. The mostly hanging nest starts from a petiole extending towards the ground. A new cell is solely attached to a corner where three adjacent walls are detected, navigating the wasps through the building process to an unknown final shape [198][193]. This “asynchronous automaton” serves as inspiration for mobile autonomous assemblers manipulating discrete elements. The logic of such assembly processes can follow rules very similar to those followed by social wasps[199].

Additional examples of swarming intelligence exist and include fireflies, locusts, bees, and other animals[182]. In this section, the author highlighted the most commonly used ones relevant to this dissertation. The relevance of swarming intelligence does not lie only within the control of mobile robots, but its concepts can employed, for example, in solving the shortest walk or Hamiltonian path definition by use of the ant colony algorithm, collision detection of boids, or for asynchronous automata logic in the case of social wasps.

3.2.3 Cellular automata

Cellular automata have had several applications within different disciplines, including architecture, and became popular mainly over the last two decades, when discrete oriented architecture began searching for what could be automatically generated based on simple rules. Cellular automata are represented by cells in a regular grid. Each cell has predefined states which define how the cell will act according to its neighbourhood. The rules remain the same during a discrete time period, but new states of cells are updated with every new generation. Most examples follow a rectangular grid (1D, 2D, or 3D). 2D grids have been investigated most intensively. In 2D cellular automata, two main neighbourhoods are defined: the Von Neumann neighbourhood and the Moore neighbourhood:

- A Von Neumann neighbourhood is defined by four surrounding cells, each with one common edge.
- A Moore neighbourhood is defined by eight surrounding cells where four have a common edge with the investigated cell and where four have one common vertex with the investigated cell.

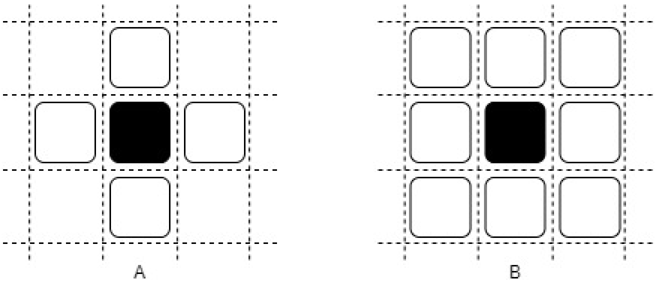


Fig. 16. (a) Von Neumann neighbourhood, (b) Moore neighbourhood

The original idea of cellular automata was already developed in the 1940s and 1950s by von Neumann and Ulam from Los Alamos National Laboratory. The concept stems from self-replicating theories and systems developed by von Neumann [200]. Cellular automata (CA) gained great interest twenty years later in 1970 when Conway introduced his two dimensional *Game of Life* [201]. Later, Wolfram developed a one-dimensional CA called *rule 30* [202] and Langton, *Langton's loops*[203]. For the scope of this dissertation, CA plays an important role in the context of self-reconfigurable modular robots.

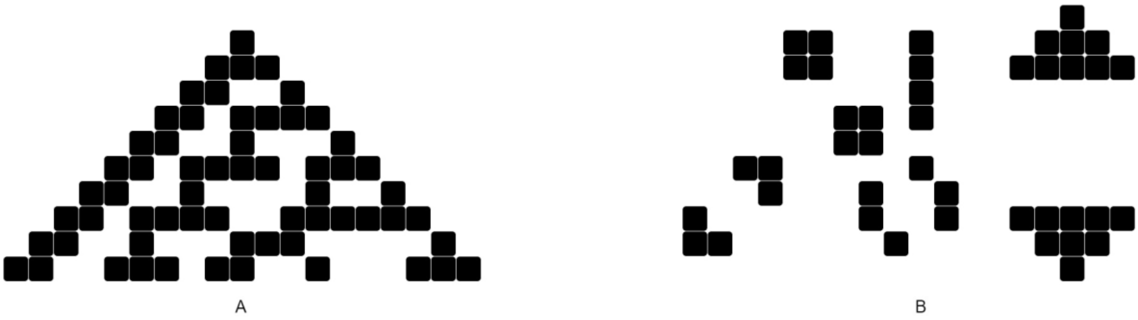


Fig. 17. (a) 1D Cellular Automata (Rule 30), (b) 2D Cellular Automata (Game of Life).

Self-reconfigurable modular robots follow 3D or 2D regular grids (mostly cubic or square) in which a new position for a robot is defined according to the current state of a module, similar to CA. The performance of a modular robot is based on its design (e.g., connection, shape, hinges) that defines its possible next state through a set of certain rules. To accomplish motion planning, cellular automaton has been investigated as a tool for decentralized modular robot control [204]. Cellular automatons simulating fluid systems are being used to help determine the motion of the several modular robots and their interaction with an environment, including different types of obstacles. This was investigated by Butler et al. [204], where a water flow algorithm was used as a tool to accomplish movement on a surface including obstacles while the modular robot structure remains connected. This was especially noteworthy because a 1D modular robot was used to define rules [204].

Cellular automata have been widely used over different disciplines applicable to architecture. The most promising application in architecture remains in generative design, especially city planning. *Michael Batty Cities and Complexity* [205] describes how cellular automata accompanied by agent based systems or fractals were used for analysing and predicting city development. The popular *Cellular Automaton Game of Life* was also used by this author in the 2014 Re-adaptive-city project, in which massive platforms for apartments were adapted according their surroundings [206] (Fig. 18).

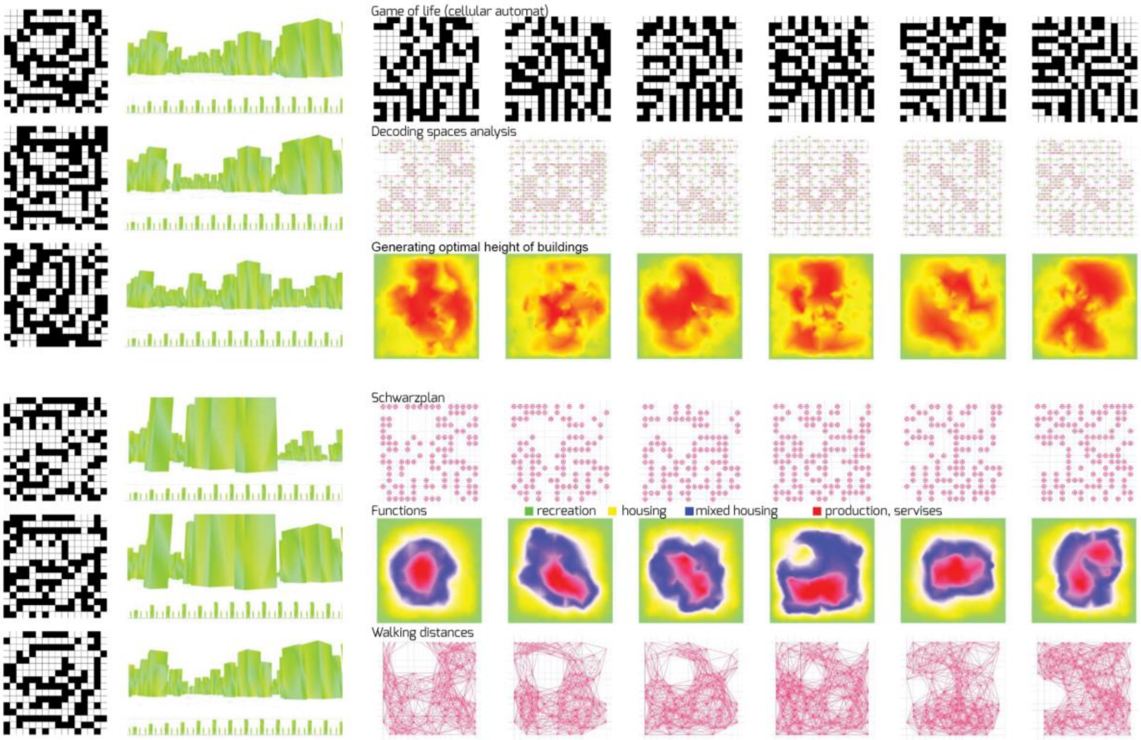


Fig. 18. Use of adopted cellular automata "Game of Life" for generating a real time urban plan that constantly evolves, and adapts, and analyses. The city consists of a movable massive platform that can move according to the "schwarzplan" generated..

3.2.4 Self-organisation summary

Self-organisation, especially swarm intelligence, is widely used for control of mobile robots used in some architectural projects [207] and has, in recent years, become more popular as a design technique [208]. Through different simulations of swarming intelligence or agent-based systems, an architectural object can be generated. Such techniques were used in the author's master thesis, "Swarm Tower" (Fig. 15). Ever since architects introduced small scale mobile assemblers (described in Section 4.2) into the building design process, self-organization has been used for their control, as seen in Petersen and Nagpal's Termes project [7]. Self-organisation has been present in building activities since humans built their first dwellings, with examples seen in slums, first colonies, villages, and in some of the historical cores of today's cities [205]. Many old agglomerations were generated by the natural needs of inhabitants, not by central planning as in modern cities. Such urban structures were constantly adapting to new needs springing from the bottom to the top.

3.3 Self-replication and self-reproduction

To fulfil all the possibilities of reconfigurable modular systems, self-replication/reproduction cannot be neglected. Self-replication refers to behaviours that an object can make to produce an exact copy of itself. Often it is wrongly used as a synonym for self-reproduction. Reproduction is the ability to produce a similar object influenced by evolution [209]. Self-replication has been investigated in different disciplines such as biology, computer science, and robotics. For example, the replication of cells, viruses, and DNA molecules is essential for living organisms and served as the inspiration for engineers and computer scientists in creating self-replicating machines and software.

3.3.1 Universal constructor

Self-replication was originally investigated by von Neumann in relation to the development of cellular automata, as discussed in the previous section. The impact of von Neumann influenced all later generations investigating self-replication systems. The most well-known of von Neumann´s investigations is the concept of a self-replicating machine, the Universal Constructor, developed in a cellular automata environment in the 1940s. The Universal Constructor is a machine capable of building any configuration as well as an identical copy of itself with a "construction arm" following instructions stored on a

“Turing tape” [200] (Fig. 18). Later, the Universal Construc tor was further explored by computer scientists, including Codd and Devore, who optimized and simplify the estimation of 50,000 to 20,000 cells [209].

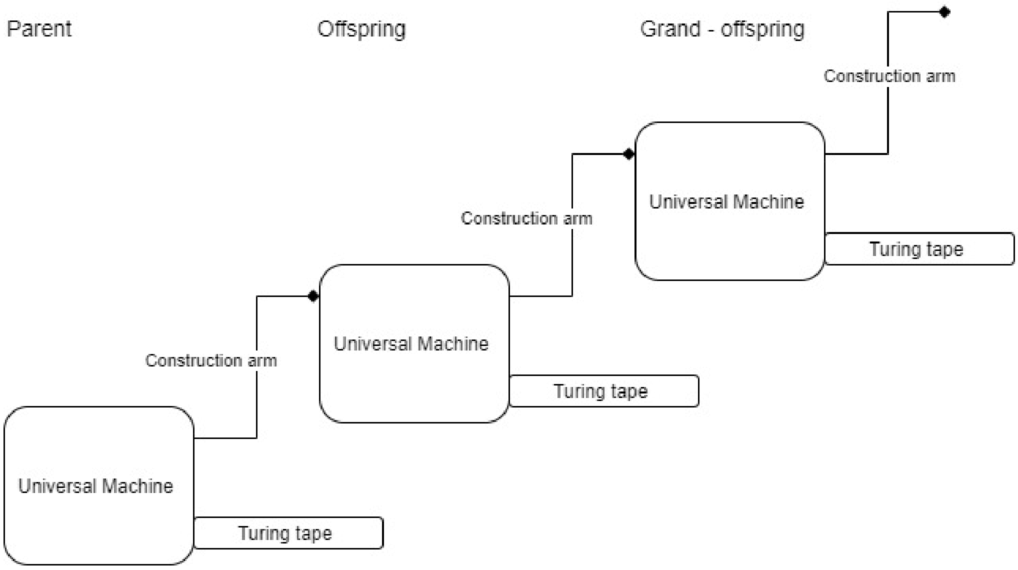


Fig. 19. Simplified principle of von Neumann´s Universal Constructor adapted from [209].

3.3.2 Self-replicating wooden blocks

In 1958, Lionel Penrose and his son Roger introduced the concept of mechanical, self-replicating wooden blocks [210][211]. The idea builds upon von Neumann’s work with artificial crystals. The blocks had predefined types of connections accompanied by magnets and hooks, with different configurations indicating if the hooks were activated or not. This formed individual blocks into specific groups, which then created copies of themselves based on rules defined by the positions of the hooks (Fig. 20). The energy necessary for the forming process was provided by shaking when the blocks were moved in horizontal direction as they were assembled. The blocks in their neutral state could not join into groups. Solely by changing their configurations (adjusting hooks or simply flipping early stage blocks), all the blocks formed into new patterns. Penrose`s blocks showed how replication could be applied to physical blocks reminiscent of building materials [6]. During his experimenting, Penrose introduced more complex blocks able to connect in large groups or hybrid groups. Building on his work were Jacobson’s replicator made of toy trains [212] and Morowitz’ floating duplicating machine [213][209].

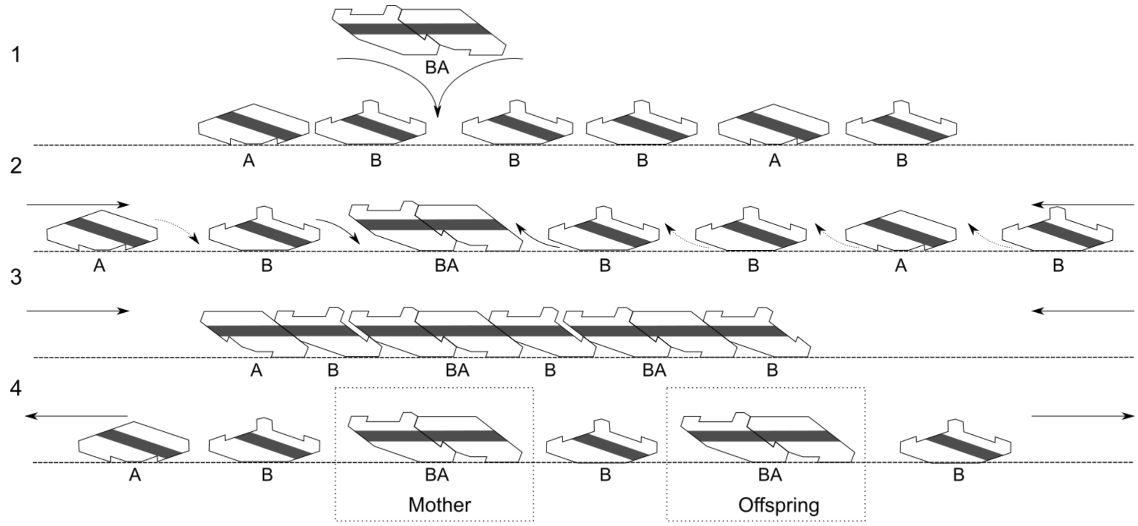


Fig. 20. Lionel Penrose's self-reproducing wooden blocks: 1. Neutral block position, 2. Adding of hooked block (BA), 3. Shaking towards replication, and 4. Replication (Mother/Offspring). Adapted from [6], [210], [211].

3.3.3 Self-replicating robots

In 2005, Hod Lipson together with graduate students V. Zykov, E. Mytyliainos, and B. Adams developed modular robots and a control system able to replicate. Prior to this, self-replication had mostly been demonstrated through simulation or theoretical works with a few exceptions such as those described in the previous section [211][210] [212]. Lipson's team created so-called "Molecubes" consisting of two halves connected by a diagonal axis around which they revolved. Each module had a microcontroller. These modular robots formed into 3-module chain configurations capable of creating identical copies of themselves by "feeding" other modules situated in two feeding areas. Lipson promoted through his work the concepts of self-awareness, self-evolution, and self-learning: the robots had to discover their own ways for moving in an environment, protecting themselves against predators, replicating, and so on.

3.3.4 Summary: self-replication towards architecture

Self-replication or reproduction can be employed in architecture in such a way that building blocks are first formed into larger machines with more degrees of freedom and operating size then one individual block would have. In a second step, these machines could build other machines. In a third step, the machines could build a final product. Let's imagine the context of an industrial robot assembly line in which the operating robots are not assembled off-site but rather on-site by neighbouring robots as copies from the same discrete parts. Even if this sounds like science fiction, this idea has been already partly applied in the context of RepRap 3D printers, where a new 3D printer is printed by another 3D printer [214]. 3D printing has been widely used also in architecture, as is commonly known, and is highly appreciated in hard-to-reach places where it is difficult to transport building blocks and use local sources [215].

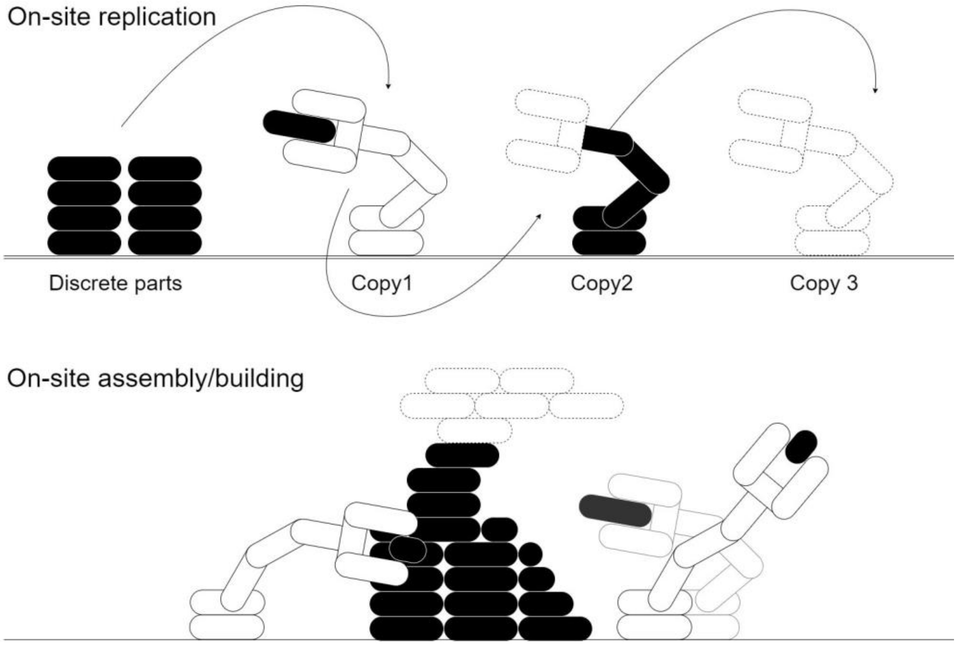


Fig. 21. Idea for self-replication on a building site.

3.4 Summary of emergent systems

All the three types of emergent systems (*assembly, organisation, and replication*) are essential background knowledge needed for the future development of the field of reconfigurable building structures. The selected examples showed novel ideas of how the systems predominantly observed in chemistry and biology can be mimicked and applied to architecture. This section included several recommendations to assist readers in the design of distributed reconfigurable architectural systems, especially when their design scale has been significantly changed. To achieve all complex building functions by using just one discrete element with only one type of emergent systems is exceedingly difficult and does not seem feasible for the near future. To further demonstrate combinations of other concepts (swarm intelligence, assembly, replication) being applied to within one system/task, readers are referred to the author's "Phagocity" project (2014) presented in

Fig. 22. The following Chapter 4 extends the concepts introduced here to recent developments of distributed robot systems.

Fig. 22. Phagocity, developed by the author, simulates a visionary idea in which robots collect a plastic trash from oceans, which they use as a material for their replication. (1,) Robots (agents) searching for garbage (food) following swarming intelligence based on boids, (2.) After collecting garbage, they double in size and start to replicate, (3.) When the colony reaches 50 members in size, members start to build desired structures from themselves, (4) Structure is completed and can be used as a platform for living.

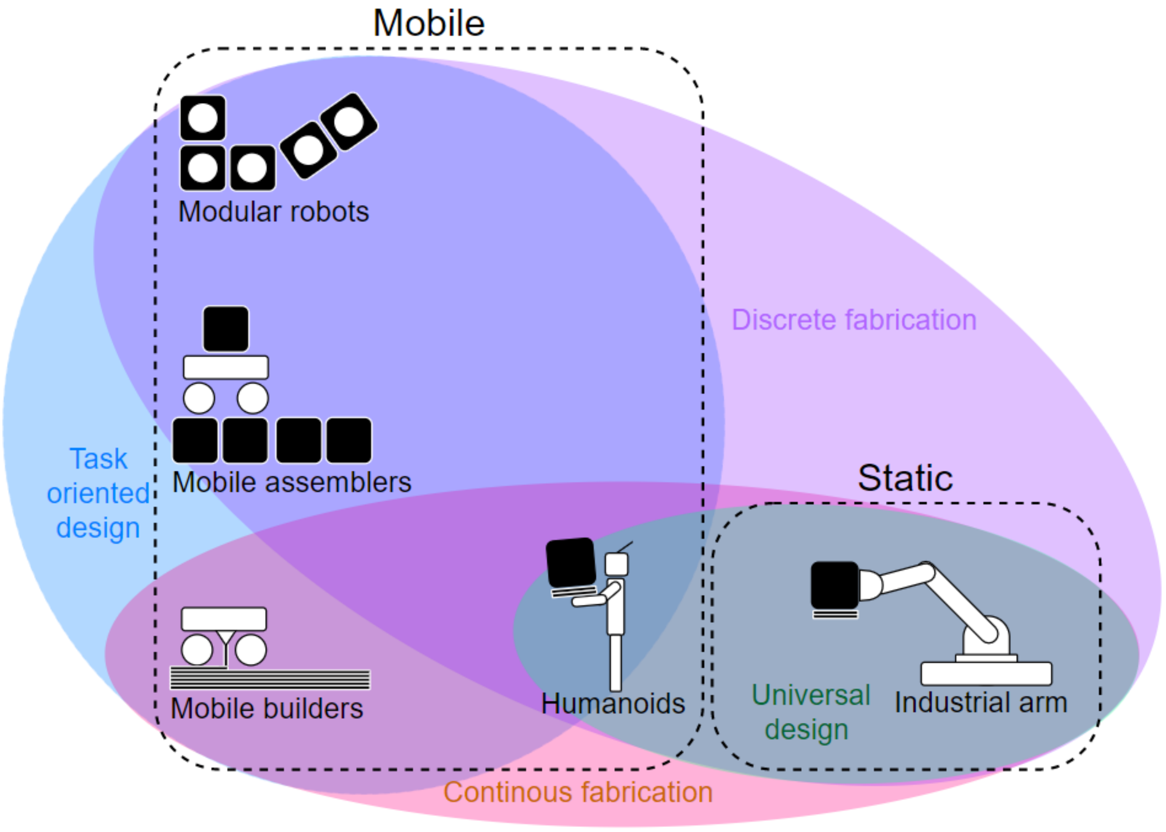


Fig. 23. Robot types which could be used in architectural implementations.

Chapter 4.

DISTRIBUTED ROBOT SYSTEMS

Before distributed robotic systems captured the interest of architects, they were topics of study in computer science, biology, chemistry, logistics, and robotics (see Chapter 3) in relation to activities such as navigation, rescue, cleaning, and research (in chemistry, biology, and computer science, for example, robots have sometimes been developed just to help understand collective behaviour by using physical devices).

Distributed architectural robot systems are the reaction of a sole group of architects not satisfied by the automatization of building processes by means of industrial arms. Industrial robotic arms were essentially designed to be used in repetitive, standardized industrial processes. This stands in conflict to the amount of unique elements typically used in architectural projects. Unlike manufacturing settings, architectural implementations often rely solely on on-site fabrication and exposure to weather conditions. The limitations of industrial arms in terms of operating volume, weight, and poor adaptivity have forced architects to use distributed robotic systems designed for specific tasks. Such tasks are performed by means of “bottom up” logic in which multiple robots cooperate in a way similar to termites building their nests (Section 3.2.2) or proteins folding into their native forms (Section 3.1.2.2). Distributed robots used in architecture can be grouped into three main types: modular reconfigurable robots, mobile assemblers, and mobile builders.

- *Modular reconfigurable robots* are part of a final structure and are considered to be a building material capable of reconfiguring a structure during its lifecycle. Their behaviour is similar to the folding of proteins or crystallization of polymers on the molecular scale (Section 3.1.2)[128], [136].
- *Mobile assemblers* distribute discrete materials (e.g., blocks) in a manner similar to the stigmergic behaviour of ants or termites when building their nests (Section 3.2.2)[185], [195].
- *Mobile builders* build inseparable final structures. Such robots use continuous materials similar to social wasps building their nests (Section 3.2.2.4) [216].
- A speculative use would be the deployment of *humanoid robots* who distribute their tasks through cooperation, not just individual work, with other humanoids[217]. Otherwise, *humanoids* are not designed specifically for tasks

(including architectural tasks) but rather are intended to copy humans. For this reason, humanoid robots are beyond the scope of this dissertation.

In this section, these three types of distributed robotic systems are discussed and evaluated. Such systems are not fixed on the ground in a specific position, as industrial arms would be; rather, they move around an operating environment or a built structure. Typically, they are smaller and lighter than industrial arms, which makes it easier for them to reach different spaces. The potential use of these types of robotic systems in architectural implementations is additionally discussed, with modular reconfigurable robots being the focus of this dissertation.

4.1 Modular reconfigurable robots

The increased use of robots in different fields has led to questions regarding their limited shapes and flexibility in performing tasks. Most robots are designed for one specific task that is repeated on a fixed place (e.g., industrial arms) or semi-repeated, mobile tasks (mobile assemblers/builders). Universality in performing tasks is often provided by exchanging so-called "end-effectors" which enable tasks such as selecting and carrying, welding, and milling [67], [87]. Modular reconfigurable robotic systems consist of several modules capable of adapting to different shapes and functions. Predominantly identical modules work through local interactions within neighbouring modules. Such robots do not have one specific function but can "morph" according to different scenarios. Imagine a robotic arm which would not be limited by its significant size but which could transform itself and crawl or climb up a staircase, or even snake through a keyhole to reach the room in which it would operate. Such concepts may seem like science fiction, but recent developments show that real-world implementation of such scenarios is just around the corner.

In 2007, the key challenges and characteristics of such types of robots were identified by Yim et al. [218] and later investigated in-depth by Ahmadzadeh et al. in their MITE framework [112]. Both works identified certain characteristics necessary as well as challenges for use of modular reconfigurable systems in architectural settings. Regarding the scope of this dissertation and its emphasis on architecture, design-mechanical aspects are discussed whereas control systems and algorithms are mentioned only marginally.

The following specifications were used in order to select the modular robots discussed in this dissertation.

4.1.1 Architecture (of robots)

A key aspect for modular robot design is the architecture used to design a system and this determines how individual modules "interface" with one another [112]. This is crucial for the end behaviour of an entire system. The three main design types currently used include lattice, chain, and mobile architectures[112]. These are accompanied by truss, origami, freeform, and hybrid architectures [112], [218], [219].

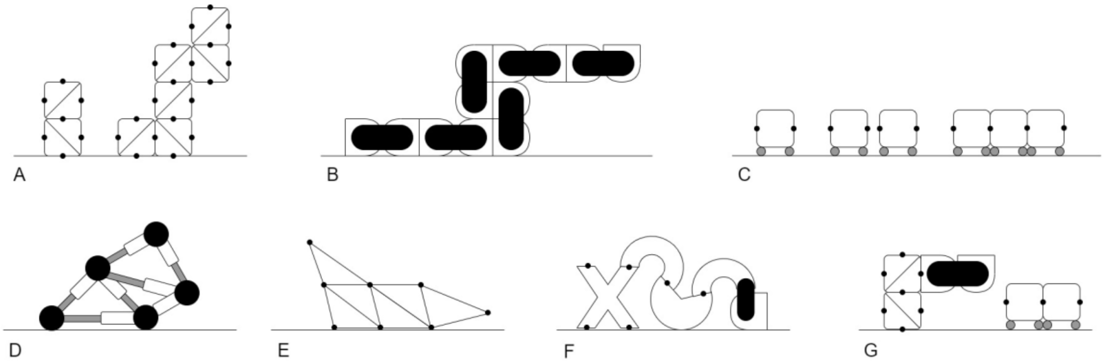


Fig. 24. Modular robot architectures: (a) Lattice, (b) Chain, (c) Mobile, (d)Truss, (e) Origami, (f) Freeform, (g) Hybrid.

4.1.1.1 Lattice architectures

Lattice architectures consist of several modular robots placed on a two-dimensional or three-dimensional regular grid [112][218]. Modules reconfigure themselves solely through their interactions with neighbouring modules. Modules are usually completely detachable from a system. Typical representantives of lattice architectures are MIT's "M-blocks" [220] or the "Roombots" developed at the Swiss Federal Institute of Technology in Lausanne (EPFL) [221].

4.1.1.2 Chain architectures

Chain architectures consist of several identical modules that are permanently connected in one long chain or in a tree structure[112], [218]. The structures reconfigure themselves into two- or three-dimensional formations similar to folded proteins. Chain systems are complex in terms of control and have a limited number of reconfigurable states, but are typically simpler (particularly in terms of joints). Chain architectures often involve space-filling geometrical methods such as Hilbert curves or Euclidean paths [120]. Examples include MIT's "Milli-Motein" [222] and the Tokyo Institute of Technology's "M-TRAN" [223].

4.1.1.3 Mobile architectures

Mobile architectures consist of elements (modules) capable of moving on their own without the need to mechanically interact with other modules. Typically, they have embedded wheels for movement on the ground or, as drones, are equipped for assembly in the sky. Mobile connections are similar to those employed in lattice-based systems [112] that enable formation of regular or irregular structures. Advantages of mobile architectures include versatility of movement. Typical examples include the swarming "Kilobots" developed by the Wyss Institute for Biologically Inspired Engineering or ETH Zurich's "Distributed Flight Array."[224]

4.1.1.4 Truss architectures

Truss architectures are usually permanently-interconnected structures made of modular struts or "pistons". Regular structures are changed into irregular ones by changing the dimensions in the longitudinal direction of the struts[225], which meet in a joint element. Truss designs are often remarkably simple but may require manual assembly before reconfiguration is possible and may have a limited range of reconfigurations[225]. Truss structures are useful for predefined tasks. An example of this type of design is the "Odin" robot developed at the University of Southern Denmark [226].

4.1.1.5 Origami architectures

Origami architectures are based on the folding of regular or irregular discrete surfaces from 2D into 3D objects. In regular cases in which individual triangles are detachable, origami designs can be interpreted as being lattice-based[218]. An example of origami architecture is the "Mori" robot from Swiss Federal Institute of Technology in Lausanne (EPFL) [219].

4.1.1.6 Hybrid and freeform architectures

These two types can combine different features from the aforementioned architectures but their shapes are not defined by any matrix and are, rather, freely formed[112].

4.1.2 Connections

Connection types can greatly influence the behaviour of modular reconfigurable robotic systems and their quality and design determine the possible applications, robustness, and versatility of any system. This dissertation describes five relevant connection features: their levels of independence, connecting mechanisms, connecting genders, numbers of interconnecting faces, and positions of their axes of rotation.

4.1.2.1 Levels of independence

"Levels of independence" refers to how much a connecting system is independent from an external manipulator, artificial or human. Three levels (fully autonomous, semi-autonomous, or external) have been determined. A fully-autonomous level is used in systems which can autonomously connect to a desired structure without any external help or preparation[227]. A semi-autonomous level is used in systems which require certain preparation before they start the process of so-called "self-reconfiguration" (e.g., manual connection of modules into larger clusters) [228]. A manual level is used for systems which are connected solely by external input such as truss architecture[229][226].

4.1.2.2 Connecting mechanisms

The most common connection mechanisms are mechanical latch-catch systems, magnet/electromagnet connectors, and complementary shape connectors[112]. Connecting mechanisms plays significant role in lattice architectures and in systems with a fully autonomous level of independence.

4.1.2.3 Connecting genders

The term "connecting genders" refers to the complementary shape of connectors, screws, or threads or the polarity of the magnets, which are typically either "gendered" or "genderless" [112]. Gendered connectors use "male" or "female" connectors and one of each is part of a connected modules. Gendered connections are often magnets, Velcro, or latch-catch mechanisms. Gendered connections can limit an entire system because only one combination (female and male) works and modules with identical genders (male-male, female-female) cannot be connected [230]. Genderless connectors are more versatile and generally recommended for use, but they require higher design effort compare to gendered ones.

4.1.2.4 Numbers of interconnecting faces

"Numbers of interconnecting faces" refers to how many faces of module can be connected. These include every mechanism designed for the connection between two modules; neighbouring faces which only touch one another in a configuration are not considered[119].

4.1.2.5 Positions of axes of rotation

Modular robots are reconfigured predominantly by a rotational movement around a certain axis in module (except for truss architecture). This aspect defines a position of axis of rotation for a module and four main types have been defined: connecting face normal, non-connecting face normal, diagonal, face edge (Fig. 25). Rarely, systems which have a centre of rotation outside a module can be found; for example, crystalline robots [231]. Systems like Kilobots [232] are considered to be non-rotational because of their special connecting mechanisms or lack of connections.

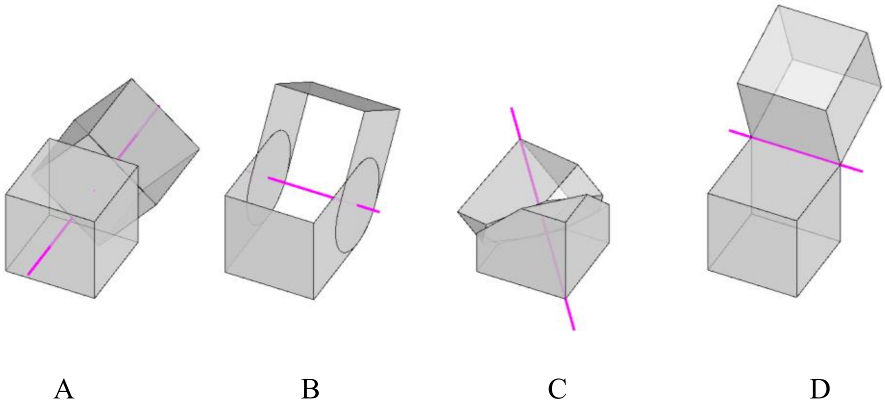


Fig. 25. Positions of axes of rotation: (a) Connecting face normal, (b) Non-connecting face normal, (c) diagonal, (d) Face edge.

4.1.3 Module level of activity

"Module level of activity" refers to whether or not a system also works with passive modules, modules which are not equipped with any mechatronic parts[119], [221]. The function of passive modules is to fill the space in configurations which do not have to be active or which help move active modules. Two types have been determined: fully active (all the modules are mechatronized-active)[231], [233] and partly passive (system combines passive and active elements) [221]. Active modules are subdivided into single[231] and multi-types[233] which describes diversity of active parts.

4.1.4 Dimension

The term “dimension” refers to the space in which robots can operate. It can be two-dimensional (2D)[232] or three-dimensional (3D) [220]. 2D systems are usually simpler than 3D systems; often, a 2D system represents a 3D concept[231]. 2D systems mostly operate on an XY plane[232] and, for architecture, movement along an YZ or XZ plane might be useful for reconfigurable façade systems. 3D systems are more complex but operate across all three dimensions, which is often the goal for architects who wish to employ robots in self-assembly building systems [119].

4.1.5 Keeping horizontal

“Keeping horizontal” is an aspect that is important for conceiving modular robots that can transform themselves into larger building units which can be inhabited from the inside, particularly during their reconfiguration[206]. To the best of my knowledge, only 2D modular robot systems retain a horizontal position during reconfiguration.

4.1.6 Degrees of freedom

“Degrees of freedom” determine the number of directions and rotations defining a position of one module[112]. The larger number of degrees of freedom makes system more versatile and complex.

4.1.7 Evaluated modular reconfigurable robots

Twenty self-reconfigurable modular systems have been selected and are described below based on the features described in Sections 4.1.1- 4.1.6. Selection was based on perceived versatility and possible use in architectural applications and led to the development of the original MoleMOD robots described in Chapter 6, and 7. A broader list of self-reconfigurable modular systems appears in Ahmadzadeh et al.[112]. Table 2 also includes two types of original MoleMOD robots which were developed for this dissertation.

Year	Name	Authors/Institution/Country	ARCHITECTURE: **L** - Lattice, **C** - Chain, **M** - Mobile, **T** - Truss, **O** - Origami, **F** - Freeform, **H** - Hybrid	LEVEL OF INDEPENDENCE: **Fa** - Fully autonomous, **Sa** - Semi Autonomous, **E** - External	CONNECTING MECHANISM: **Mech** - Mechanical, **Mag** - Magnetic, **Com** - Complementary shape, **Pneu** - Pneumatic, **Hyd** - Hydraulic, **Oth** - Others	CONNECTING GENDER: **G** - Gendered, **Gl** - Genderless	NUMBER OF INTERCONNECTING FACES	POSITION OF AXIS OF ROTATION: **Cfn** - Connecting face normal, **Nfn** - Non-connecting face normal, **Fe** - Face edge, **D** - Diagonal, **O** - outside, **N** - Non-rotational	MODULE LEVEL OF ACTIVITY: **Fas** - Fully active-single type, **Fam** - Fully active-multiple types, **Pa** - Partly passive	DIMENSION: **1D** - one dimensional, **2D** - two-dimensional, **3D** - three-dimensional	KEEPING HORIZONTAL: **Yes**, **No**	DEGREES OF FREEDOM	ENVIRONMENT: **Te** - Terrestrial, **Ae** - Aerial, **Aq** - Aquatic
				CONNECTION									
1988	CEBOT	Fukkuda et.al / Nagoya University/Japan	M	Fa	Mech	G	2	NFN	Fam	2D	Yes	2	Te
1993	Polypod	Yim / Stanford / USA	C	Sa	Mech	G	2	Fe	Fam	3D	No	2	Te
1996	Tetrobot	Hamlin et.al / Rensselaer Polytech. Inst. Troy / USA	T	E	*	*	2	O	Fam	3D	No	1	Te
1998	Molecule	Kotay, Rus / Dartmouth College / USA	L	Fa	Mech	G	10	Cfn (Nfn)	Fas	3D	No	4	Te
2000	Crystalline	Vona, Rus / Dartmouth College / USA	L	Fa	Mech	G	4	N	Fas	2D	Yes	4	Te
2000	M-TRAN	Murata et.al /Tokyo Institute of Technology/Japan	H	Fa	Mag	G	6	Cfn	Fas	3D	No	2	Te
2004	Atron	Jorgensen et.al / University of Southern Denmark/ Denmark	L	Fa	Mech	G	8	Fe	Fas	3D	No	1	Te
2005	Molecube	Zykov, Lipson / Cornell University / USA	H	Fa	Mag	GI	2	D	Fas	3D	No	1	Te

2005	Superbot	Shen et.al / University of Southern California / USA	H	Fa	Mag	G	3(6)	Cfn	Fas	3D	No	3	Te
2007	Miche	Gilipin et.al / Massachusetts Institute of Technology / USA	L	Sa	Mag	G	6	N	Fas	3D	No	0	Te
2008	Odin	Lyder et.al / University of Southern Denmark/ Denmark	T	E	Com	G	12(2)	N	Fam	3D	No	3	Te
2008-2013	Symbrion	Eu project	M, H	Fa	Mech	G	4	Cfn	Fam	3D	No	2	Te
2009	Roombot	Sproewitz et.al / Ecole Polytechnique Fédérale de Lausanne / Switzerland	L	Fa	Mech	G, Gl	6	D	Pa	3D	No	3	Te
2010	Kilobot	Rubenstein, et.al / Wyss Institute / USA	M	Fa	O	Gl	∞	N	Fas	2D	Yes	1	Te
2011	Distributed Flight Array	Oung, Andrea / ETH Zurich / Switzerland	L	Fa	Mag	G	6	N	Fas	2D(3D)	Yes	4	Ae
2012	Milli-Motein	Knaian et.al / Massachusetts Institute of Technology / USA	C	Fa	Mech	*	2	D	Fas	3D	No	1	Te
2013	M-Blocks	Romanishin et.al / Massachusetts Institute of Technology / USA	L	Fa	Mag	G	6	Fe	Fas	3D	No	4	Te
2016	Mori	Belke, Paik / Ecole Polytechnique Fédérale de Lausanne / Switzerland	O, M	Sa	Mech	Gl	3	Fe	Pa	2D	No	3	Te
2017	V-SPA	Robertson, Paik /Ecole Polytechnique Fédérale de Lausanne / Switzerland	C	E	Com	G	2	Fe	Fas/m	1D	No	3	Te
2017	Soft Modular Robotic Cubes	Vergara, et.al/ Universidad de Chile/ Chile	H	Sa	Mag	G	6	Fe	Fas	3D	No	1	Te, Aq
2018	MoleMOD I-III	Petrš / Czech Technical University in Prague / Czech Republic	L	Fa	Mech/Mag	Gl	6	Fe	Pa	3D	No	3	Te
2019	MoleMOD IV-V	Petrš / Czech Technical University in Prague / Czech Republic	C	Sa	Mag	G	6	Fe	Pa	3D	No	3	Te

Table 2. Characteristics of state of the art modular reconfigurable systems.

4.1.7.1 CEBOT

The CEBOT (Cellular Robotic System) was the first modular reconfigurable system introduced by Fukuda in 1988 [233]. Individual mobile cells (later called “modules”) were able to arrange themselves automatically into universal mobile or fixed-based manipulators by means of hooking and docking mechanisms. CEBOT was designed as 2D and cells moved on an XY plane based on an autonomous decentralized control system.

4.1.7.2 Polypod

Polypod was the first robot to operate in three dimensions [229]. The robot consisted of two types of modules, “segments” and “nodes”, each of which had two degrees of freedom. While the Polypod was considered to be fully active, the main part of the electronics system was accommodated inside a segment and nodes only the batteries and thus, it was very similar to effective *partly passive* systems[119], [221]. This concept of reduction of the number of active parts was later used in the creation of Roombots [221] and MoleMOD [109].

4.1.7.3 Tetrobot

Tetrobot as the first robot to use truss architecture [225]. The overall structure consisted of links, CMS joints, and actuators which could be manually connected to certain reconfigurable structures according to required tasks. The concept of combining links and nodes to achieve relatively large and lightweight structures is applicable to construction engineering and implementations in which overall space does not need to be filled by mass like truss elements.

4.1.7.4 Molecule

“Molecule” represented a lattice-based architecture system and consisted of two identical “atoms” linked by a “bond” mimicking a molecule [234]. The “atoms” rotated relative to a bond in order to facilitate a “transition”, with five mechanical connections in each “atom.” Molecule had a complicated shape which, to tie back to architectural implementations.

4.1.7.5 *Crystalline robots*

Crystalline robots are unique 2D lattice-based systems that uses contraction and expansion for reconfigurations instead of often used rotation. The original crystalline robot was built in 2000, with one-dimensional and 2D versions[231]. Each module has two active and two passive connecting faces which move facing normal directions in order to complete individual assembly steps. Crystalline robots are one of the best examples of modular reconfigurable robots in terms of holding promise for architectural implementations; the replacement of rotational movement could even allow them to be transformed into a horizontal position making them "liveable" [206]. In 2013, the author of this dissertation transformed crystalline robots to demonstrate the concept of large-scale, permanently adapting building blocks in the "Re-adaptive city" project [206](Fig.26).

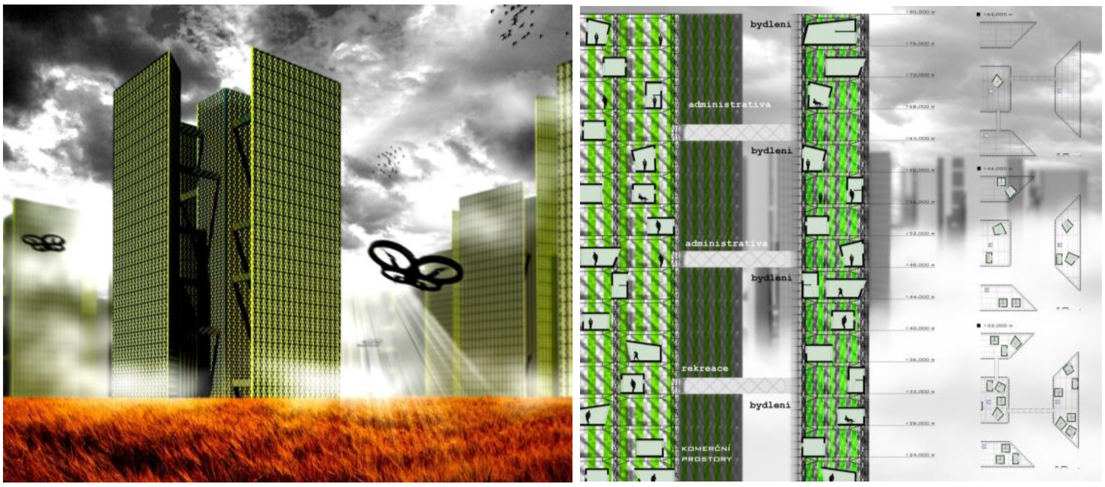


Fig. 26. "Re-adaptive city" project transformed crystalline robots to large-scale, permanently adapting building blocks

4.1.7.6 *M-Tran*

"M-tran" was a hybrid system in which individual modules were connected via chain architecture [223]. Individual modules, shaped like the letter "D", had two curved sides which slid on each other with a help of an interconnecting link, with the other sides having permanent magnet connections. M-Tran represented a type of geometry which, with its simplicity, could be applied to architectural implementations and exhibited the advantage of having permanent guidance with clear linkage between modules which exactly defined the assembly steps. The concept holds promise for fully manual assemble when human workers are guided by a predefined logic towards the creation of a desired structure, similar to the folding of proteins process[148].

4.1.7.7 Atron

“Atron” was a highly advanced, self-reconfigurable lattice-based system which combined two types of rotational axis: “pre-configuration” was defined by turning half of a module around a central axis (perpendicular to connecting face), and the final configuration was created by means of a hinge-like rotation around the edge of a module[235]. This combination of two types of reconfiguration allowed for a variety of configurations capable of multiple types of movement such as driving, walking, and crawling. Atron was one of the most advanced modular reconfigurable systems because of this versatile configuration ability, but was very complex and it is difficult to imagine its use at the architectural scale. However, a similar combination was used to create the passive part of MoleMOD Version 5 described in Section 7.2.3 within experiments.

4.1.7.8 Molecube

“Molecube” was a demonstrator of self-replication [236], [237] (discussed in section 3.3.3). Similar to M-tran [223], it exhibited a hybrid architecture combining lattice and chain architectures. Molecube was a simple solution with only one diagonal rotational axis along which transformation was performed. This concept was later refined in Roombot [221] and Festo Molecubes[238].

4.1.7.9 Superbot

“Superbot” had a hybrid architecture based on principles similar to M-Tran [223]. Superbot was designed for NASA space exploration programs[227]. Robot was capable to perform locomotion and reconfigurability in uncontrolled environment with presence of obstacles and dust. The consideration of real-world environment is essential also for robot design in architectural applications.

4.1.7.10 Miche

“Miche” was a unique system developed in 2007 [228]. The configuration goal was achieved with a process called “self-disassembly” analogous to classical sculpting from stone in which cubic modules were first assembled manually into a basic structure following rectangular grid. Then, unnecessary modules were disconnected in a bottom up process in which modules communicated with one another and collectively distributed information and the remaining modules formed the desired structures. The process of self-disassembly was a discrete subtractive method which has high potential for future use in smart building materials: the absence of complex rotational movements and mechanical connections makes such a system significantly cheaper and lighter than other comparable systems[227], [234], [235]. The Miche concept also could be interesting for use in aggregate architecture [239] because of its simple and fast assembly mechanisms.

4.1.7.11 Odin

The “Odin” system consisted of four elements: a telescopic link, a passive link, a flexible connection mechanism, and a cubic closed-packed (CCP) joint module [226]. The four elements are manually interconnected into truss architecture similar to the Tetrobot from 1997 [225]. Kinematics were provided solely by the extendable telescopic link. Odin concept has the potential to be used in architecture for the building of truss-based structures or megastructures. Certain modules can also hold a horizontal position, which could eventually make such structures liveable[83].

4.1.7.12 Symbrion

“Symbrion” was a large European project charged with mimicking natural swarming systems using open source and open hardware frameworks for self-organization and self-replication[209]. The robots developed under the auspices of the project were hybrid or mobile and mechanical connections with ability to interconnect into large robotic organisms like starfish, snakes, and spiders were used [117].

4.1.7.13 Roombot

“Roombot” was designed for the creation of adaptive furniture[221]. The system consisted of cube-shaped modules split diagonally into two halves which rotated against each other towards a desired configuration, similar to Molecubes [236], [237]. One of the most advanced modular reconfigurable systems developed to date, Roombot combined active and passive modules following a lattice grid, making the concept cost-effective and lighter. Roombots have potentially very interesting applications within architectural systems thanks to the rotational movement of their two halves, which makes modules mobile and able to move with objects such as furniture.

4.1.7.14 Kilobot

“Kilobots” enabled the building of complex forms by several self-organizing robots mimicking natural swarming systems like flocks of birds and schools of fish [232]. The Kilobot system was a 2D mobile system consisting of 1,024 units, the largest number of modules used within a modular reconfigurable systems when it was created [232]. Cylindrical mobile units (diameter of only 33 mm each) moved on an XY plane with controlled vibration motors, communicating with one another with infrared light [232]. The Kilobot concept has a high potential for use in architecture. With it, one could imagine “swarming” façade components which could provide adaptive shading by moving into certain positions (Fig. 27). Kilobots are also simple and cheap, costing under 15 dollars.

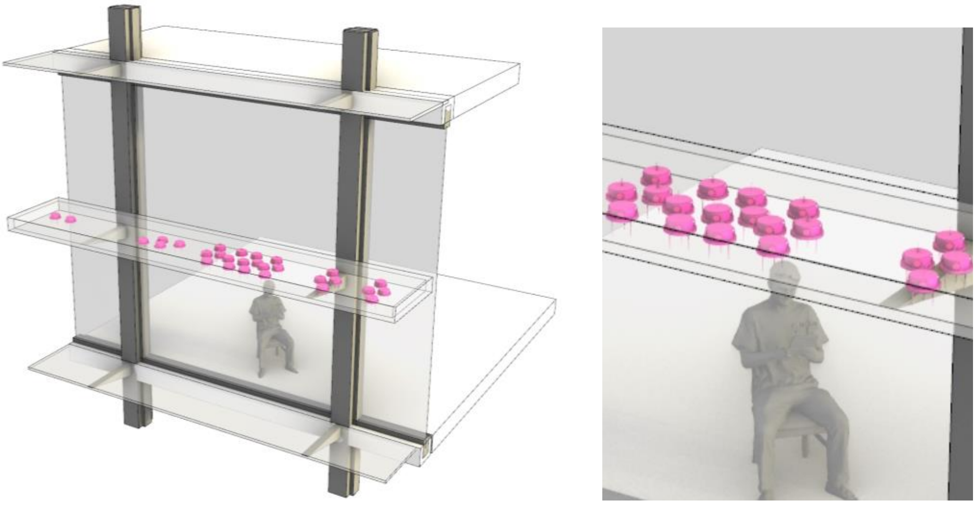


Fig. 27. Author’s idea of using Kilobots as a shading façade adaptive system

4.1.7.15 Distributed flight array

“Distributed Flight Array” was as an aerial 2D system in which individual modules were drones not able to fly without being connected to one another [224]. A magnetic connection was provided on the ground and drones were equipped with a terrestrial driving mechanism in order to first reconfigure the desired structure before a flight. Aerial systems are a large topic of discussion in the construction industry at present, but typically with regard to the distribution of building materials[240], [241]. Their disadvantage lies in their battery and payload capacities. The distributed flight array holds potential for use in architecture, especially if the interconnection of modules would be possible in the air.

With flight, several reconfiguration steps could be skipped and the process of assembly made faster when compared to terrestrial modular robots. Another advantage would be their ability to hold a horizontal position; this could eventually lead to individual blocks that were liveable.

4.1.7.16 Mili-Motein

"Mili-Motein" continued previous research in universal folding strings shapes [120]. The system used chain matter formed by programmable, ultrasmall "V"-shaped robots with 1 cm pitch [222]. The chain was permanently connected, with each robot allowed one degree of freedom by rotation around a central axis caused by electro-permanent wobble motors[222]. Mili-moteins followed space-filling curve strategies in which desired space is filled by one folded curve (similar to protein folding)[120]. This distinguished it from other systems which usually used lattice-based architecture to a similar end. The advantage of a foldable string without detachable connections is especially problematic for architectural applications, since architecture can typically be discretized into several blocks. However, for solely continuous parts such as piping and electro-installations, the foldable string concept might be useful, though it might have more configuration limitations than lattice-based systems, though it might also be significantly easier and saver to assembly than lattice-based systems and avoid hazardous disconnection from or falling of certain parts. Folding strings inspired the MoleMOD Versions 3-5 system created for this dissertation and described in Chapter 7 [119].

4.1.7.17 M-block

"M-block" consisted of individual cubic modules with 5 cm edges following a lattice-based structure bonded by magnetic forces on the edges and other magnets on the faces to provide alignment [220]. Transformation was performed by simple rotational movements around edges as well as jumping over modules into desired positions and assembly by torque-based rotation around edges[220] which enabled regular cubes to efficiently form into goal shapes. This concept could be advantageous for architecture applications in which closed walls and similar elements are necessary, but the speculative strength of connections for larger and heavier modules could be problematic.

4.1.7.18 Mori

"Mori" was developed in 2016 and is the only example of origami architecture known to the author of this dissertation at the time of writing [219]. The system consisted of two steps, mobile and reconfigurable steps. The mobile step enabled the self-organization of individual modules with a mobile apparatus to form a 2D structure. The reconfigurable step transformed the 2D structure into a 3D structure. Mori could create a static structure and also walk and crawl, among other things. The system included passive modules to reduce the overall price and could potentially be used for thin-walled folding structures in architectural applications[242].

4.1.7.19 V-SPA

"V-SPA" was a modular, semi-soft robot able to perform different task configurations with manual assembly into chain architecture [243]. Reconfiguration was provided by vacuum-assisted shrinkage of individual cylindrical modules. V-SPA provides an example of how rigid mechanisms within modular systems can be replaced by soft actuators[244] and it was adaptive, safe, and robust, which—in combination with modularity—made the system highly versatile. Its disadvantages included low precision of movements performed by soft actuators. Due to its safety reputation, the V-SPA concept holds potential for use in architectural elements which interact directly with humans and animals.

4.1.7.20 Soft modular robotic cubes

In 2017, researchers from the Universidad de Chile published an article describing cell morphogenesis with soft elastomeric cubes actuated by controlled air pressurization with the help of a permanent magnetic docking mechanism which moved with them in a lattice composition [245]. The predominantly soft modular system was controlled only by inflation or deflation, without any rigid mechanisms or electronics except for permanent magnets. Similar to V-SPA, these soft cubes took advantage of the high adaptivity of soft actuation in order to increase resistance to uncertain conditions. Like most soft actuators, the cubes did not perform quickly or precisely[244]. To fully harness their potential for architectural applications, direct interaction with natural conditions such as ground stabilization, river flow control, and so on would need to be considered.

4.1.8 Summary: Modular reconfigurable robots

It is clear from the examples above that existing robotic systems are not adapted to the purpose of adaptive robotic engineering, but there are numerous systems upon which architects can build in the future. Construction by means of modular reconfigurable robots is a very complex and usually combines several techniques and methods together. Thus, it would be naive to assume that a single robotic system would be able to perform all the tasks necessary on a construction site. Each system has certain geometrical or mechanical limitations which would need to be considered, and even discretized architectural designs need continuous parts and processes in order to function.

Based on the systems examined, five rules of thumb for creation of modular robotic reconfigurable building systems have been determined by author.

4.1.8.1 Passive and active

A system should predominantly use passive modules which move by means of interaction with active modules or mechanisms. This reduces the overall price and weight of a system and enables more material and shape options regardless of any mechatronic limitations of active parts.

4.1.8.2 Lightweight

A system should be fabricated from lightweight materials in order to reduce high power and heavy actuators in active parts.

4.1.8.3 Simple module/simple rules

It is easy to over design a system to enable as many degrees of freedom as possible, to created sophisticated connections and versatile sensing systems, and so on. However, overdesign brings with it more control and mechatronics requirements. It is good to remember that even lower degrees of freedom will also enable many possible configurations for large scale applications in which many modules are used.

4.1.8.4 Safety first

A system should be designed in a way that potential accidents (e.g., falling of parts during assembly, disconnection of a built structure) are minimized. This should be insured through sophisticated mechanical/structural designs rather than by sensing or robot control alone.

4.1.8.5 *Continuous by discrete functions*

A building consists of many continuous elements necessary for correct functionality (e.g., isolations, electro-installations). It is important to design an overall concept in a way that both discrete and continuous functions are considered.

4.1.8.6 *Robots make robot*

Goal objects do not have to be assembled only by means of basic robot behaviours/mechanisms. Basic modules/robots should have ability to form bigger machines with larger operating ranges (take, for example, cranes, industrial arms, or spider robots). Such robots could perform a broad range of construction tasks (Fig. 28).

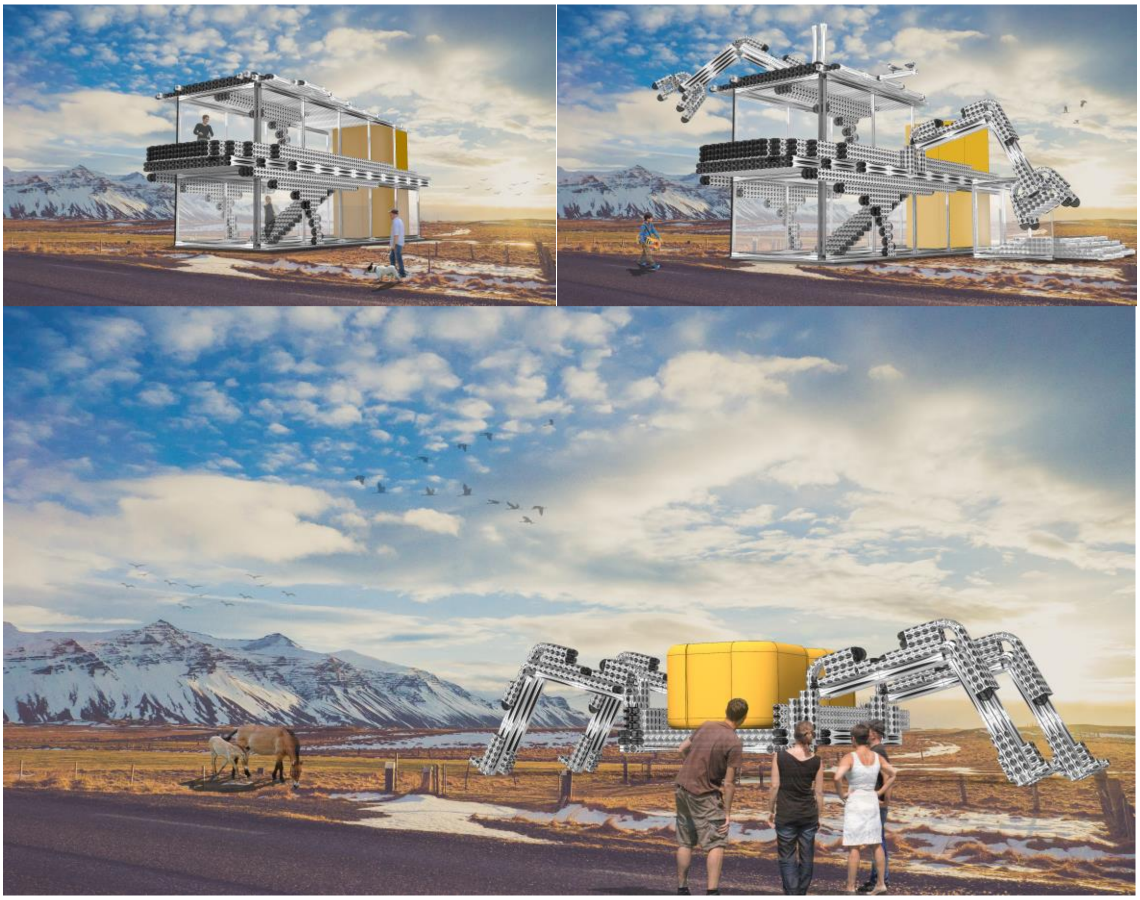


Fig. 28. Author's idea of using ability of reconfigurable modular systems to form bigger machines.

4.2 Mobile assemblers

Most of the recent architectural distributed robotic building systems employ mobile assemblers as a more feasible solution than modular reconfigurable robotic systems for discretized (modular) construction systems. The fundamental advantage of the former is that the number of active assemblers (robots) is significantly lower than the number of passive assembled elements. Such systems are more economical and lighter than modular reconfigurable robotic systems[112]. The materials and shapes of passive elements can vary and such systems exhibit universality in terms of the ability of task-oriented robots to manipulate objects and in being mobile. On the other hand, mobile assemblers are essentially grippers attached to mobile platforms (terrestrial, aerial, or aquatic) and thus can have implementation drawbacks similar to those of industrial arms, including operating accessibility, which is crucial for reconfigurable architecture and its self-assembly. Mobile assemblers operate on the outside surface of an assembled structure and this requires space for the robot itself, which limits options for system design and behaviour. The author of this dissertation refers to this as the "escape of the central element problem."

Potential solutions to the "escape of the central element problem" include:

1. Open structure: The structure is not fully closed. It is designed with gaps in-between modules that can be used for robotic operations—essential, for example, for truss-based architecture[225], [226].

2. Closed structure: The robot first removes all elements covering a central element in order to have enough access for manipulation with modules.

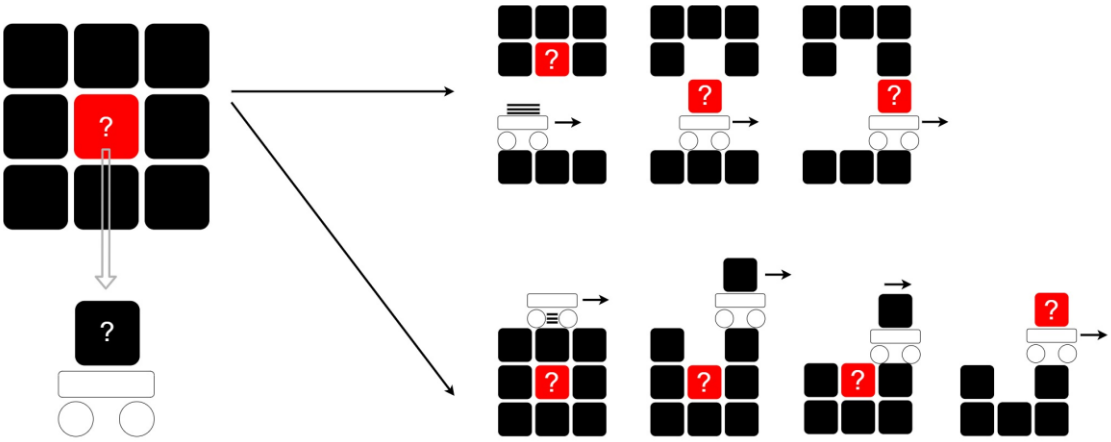


Fig. 29. "Escape of the central element problem" of mobile assemblers and two possible solutions.

The “escape of the central element problem” is fundamental for systems that will be reconfigurable during the entire lifecycle of a building/structure. If the goal is only self-assembly of a building without later reconfiguration or disassembly, this problem is—for the most part—non-existent. “The escape of the central element problem” in combination with the cost problem of modular robots were essential considerations contemplated as the author of this dissertation devised the concept of modular reconfigurable systems with sharable actuators applied to MoleMOD [109], [119].

Even though the focus of this dissertation is on modular reconfigurable systems. The most relevant state of the art mobile assemblers are described and compared since MoleMOD uses mobility of sharable actuator. The main concern is on ones which were designed for architectural tasks. These were evaluated similarly to modular reconfigurable robots in Section 4.1.

Several features were evaluated accordingly to the specifications for mobile assemblers shown in Table 3. Some of these features were adopted from an evaluation of modular reconfigurable robots (discussed in Section 4.1) like: architecture, connecting mechanisms, connecting genders, numbers of interconnecting faces, dimensions, keeping horizontal, and environment.

Additional conceptual features/characteristics included: the escape of the central element problem, assembler degrees of freedom, gripping mechanisms, types of movement.

4.2.1 Escape of the central element problem

This feature describes the typology of an assembled structure and two types have been identified: open structures and closed structures (see Section 4.2.).

4.2.2 Assembler degrees of freedom

This refers to how many degrees of freedom can be provided by one assembler (robot).

4.2.3 Gripping mechanisms

The term “gripping mechanisms” refers to how individual modules (elements) are gripped by robots.

4.2.4 Types of movement

Assemblers can move around assembled structure by using different mechanisms which are highly influenced by their operating environments. Terrestrial robots predominantly walk, climb, or ride on a built structure. The geometry of a built structure defines their movement mechanism. Aerial assemblers are typically fly independently in order to reach structure morphologies. In most cases, assembler designs are less dependent on the morphology of assembled structures compared to modular reconfigurable systems[112].

4.2.5 Evaluated mobile assemblers

				MODULE CONNECTION							ROBOT		
Year	Name	Authors/Institution/Country	ARCHITECTURE: **L** - Lattice, **T** - Truss, **C** - Chain, **F** - Freeform, **H** - Hybrid	CONNECTING MECHANISM BETWEEN MODULES: **Mech** - Mechanical, **Mag** - Magnetic, **Com** - Complementary shape, **Gl** - Glue, **Sc** - Screw **NC**- No Connection	CONNECTING GENDER: **G** - Gendered, **Gl** - Genderless	NUMBER OF INTERCONNECTING FACES	DIMENSION: **1D** - one dimensional, **2D** - two-dimensional, **3D** - three-dimensional	KEEPING HORIZONTAL: Yes, No	ENVIRONMENT: **Te** - Terrestrial, **Ae** - Aerial, **Aq** - Aquatic	ESCAPE OF CENTRAL ELEMENT PROBLEM: **O** - Open structure,**C** - Closed structure	ASSEMBLER DEGREES OF FREEDOM	GRIPPING MECHANISM: **Mech** - Mechanical, **Mag** - Magnetic, **Pn** - Pneu	TYPE OF MOVEMENT: **W** - Walking, **R** - Riding, **C** - Climbing, **F** - Flying, **S** - Swimming, **P** - Peristaltic
2011	Flight Assembled Architecture	J. Willmann et.al / ETH Zurich / Switzerland	F	Gl	Gl	2	3D	Yes	Ae	C	4	Mech	F
2011	Termes	K.Petersen et.al / Wyss Institute-Harvard / USA	L	Mag	Gl	2(6)	3D	No	Te	C	5	Mech	C
2017	Strut Climbing Robot	N. Melenbrink et. al / Wyss Institute-Harvard / USA	T	Com	G	2 + 6	2D	No	Te	O	2	Mech	R, C
2017	Cyber Physical Macro Material	ICD / University of Stuttgart / Germany	L	Mag	G	4	2D	Yes	Ae	O	4	Mech	F
2018	Distributed Robotic Assembly	S. Leder, R. Weber, et. al / University of Stuttgart / Germany	T	Sc	Gl	2	3D	Yes	Te	O	1	Mech	C
2019	Romu	N. Melenbrink et. al / Wyss Institute-Harvard / USA	F, C	NC, Com	Gl	2	1D	Yes	Te	O	3	Mech	R
2019	BILL-E	B. Jenett et.al./ MIT /USA	L	Mag	Gl	6	3D	Yes	Te	C	6	Mech	W
2018	MoleMOD I-III	Petrš / Czech Technical University in Prague / Czech Republic	L	Sc	Gl	6	3D	No	Te	O	3	Mech,Pneu	P
2019	MoleMOD IV-V	Petrš / Czech Technical University in Prague / Czech Republic	C	Mag	G	6	3D	No	Te	O	3	Mech	R

Table 3. Characteristics of state of the art mobile assemblers.

4.2.5.1 Flight assembled architecture

Flight assembled architecture, as developed by Willman et al. used cooperating quadcopters to assembly polystyrene modules with dimensions of 30cm x15cm x10cm [107]. These drones built a 6 m high free form tower composed of 1,500 bricks, a scaled model of large-scale building where individual polystyrene blocks represent building units. To the best of the author's knowledge, this is the tallest self-assembled structure built to date. The bricks were simply glued to one another, simply and cheaply, without any connecting mechanisms or special complementary shapes. The glued connections did not allow later reconfiguration. Mechanical or complementary connections could be integrated into future similar projects. Other aerial assembly research builds upon these concepts [69].

4.2.5.2 Termes

In 2011, Petersen, Nagpal & Werfel developed one of the most advanced self-organizing robotic building system created to date [7][6]. The Termes robots mimicked the collective stigmergic behaviour of termites (see Section 3.2.2.3). These task-oriented robots were designed to fulfil two main functions: climbing on a modular structure, and module gripping. The passive modules integrated tracks that guided the assemblers. The connections between modules were magnetic. The size of each foam-based module was 21.5 cm x 21.5 cm x 4.5 cm and the system was an example of a typical lattice-based closed structure. The overall design and behaviours focused on assembly without later reconfiguration, even though that would be possible through certain adjustments.

4.2.5.3 Strut climbing robot

The "Strut Climbing Robot" was a two-dimensional truss system consisting of three components: the robot, the strut, and the connector [9]. The robot with two degrees of freedom was equipped with riding and gripping systems that enabled movement over a triangular grid structure consisting of completely passive and simple wooden struts connected by a 6-face connector equipped with a force sensor. The gripper enabled picking up and placing of wooden struts into the connectors. With this open structure, the robot could access all elements which needed to be reconfigured. The Strut Climbing Robot project did not only focus on design, control, and behaviour, but it also considered structural aspects during assembly, measured by force sensors in the connectors [9]. This functionality is, in the opinion of this author, essential for future architectural applications.

4.2.5.4 Cyber physical macro material

The “Cyber physical macro material” was developed in 2018 [11] [246]. It provides a second example of aerial assembly. The lattice system focused on reconfiguring shading systems in public spaces. The octagonal shading modules were assembled in 2D cantilevering structures around central columns. The carbon fibre composite modules were attached together by magnetic connectors on four sides of each module. Compared to the Flight Assembled Architecture [241], the magnetic connections within modules allowed for easy reconfiguration later[246].

4.2.5.5 Distributed robotic assembly

The “Distributed Robotic Assembly” system (2018) focused on the assembly of simple discrete timber struts by means of simple 1-DoF assemblers [11] [8]. One gripping mechanism and its rotation enabled both manipulation and locomotion of the assemblers. Even if the robot provided only 1-DoF (rotational) during correct assembly, it could transform into a machine with multiple DoFs in order to function like an industrial arm. The universality of this configuration with a simple 1-DoF assembler makes the system highly interesting for possible use in future architectural applications.

4.2.5.6 Romu

The “Romu” system’s goal was to use terrestrial mobile assemblers in order to stabilize soil erosion by creating discrete barriers[247]. Romu could carry blocks as well as push them into the soil. This pushing was accomplished by a vibration hammer that pressed the barriers 30-40cm into the soil. The work is highlighted here because its focus was on ground implementations [247]. The general question of how self-assembly/organizing systems could connect to the ground is important. The necessity of self-assembly of ground works would be essential for fully functional future architectural applications and should be investigated more within the field.

4.2.5.7 BILL-E

In 2019 Jenett and Gershenfeld from MIT’s Center introduced the “BILL-E” assembly system [248]. The system worked as a symbiosis of assembler and voxel units that the robot manipulated and walked over. The simple robot used discretization of movement, where each step is equal to a voxel dimension. Guidance through a known environment (formed by voxels units) helped keep track of robots that did not need sophisticated navigating systems, but rather were more or less "counting their steps." The system was efficient and would be relatively simple to use in construction projects, thus illustrating a high potential for future architectural applications.

4.2.6 Summary: Mobile assemblers

Mobile assemblers have captured more attention than modular robots in the architectural community[9], [10], [241], [246], [247] . This is mostly influenced, as noted several times above, by the relatively affordable price (because they consist predominantly of passive elements and have relatively simple assemblers) of such systems. The examples above show that assemblers exhibit collective stigmergic behaviours (Section X) more than modular robotic self-assembly systems do. Based on the examples shown here, mobile assemblers can be divided into "independent" and "dependent" groups:

- *Independent assemblers* are predominantly adapted traditional or ready-made mobile systems equipped with custom-made grippers[7]. Essentially, these assemblers can work with different manipulated objects and move without assembled structures. These are typically drones [241], [246].
- *Dependent assemblers* can work only with the passive elements. These hybrid robotic systems [109] cannot separate passive elements from active ones and cannot work without both. A typical example is BILL-E [248]

The six rules *(passive and active, lightweight, simple module – simple rules, safety first, continuous by discrete, and robot assembles into robot)* for successful design of modular robots (described in Section 4.1) can be extended, based on understanding mobile assemblers, to include *discrete movement* and *guiding structures.*

4.2.6.1 Discrete movement

Discrete movement is recommended for terrestrial robots. By discretizing movement, the need for navigating and sensing systems can be reduced [248]. Discrete movements count walking steps or wheel rounds in relation to discrete assembled structures instead of using sensors.

4.2.6.2 Guiding structure

It is easier for robots to move within a described environment rather than real world environment[250]. Guiding track are recommended by author for easier navigation towards sensor reduction. In architecture these should correspond with design of built structure.

4.3 Mobile Builders

The last group of distributed robotic systems are mobile builders. They differ from modular reconfigurable robots and mobile assemblers by the homogeneity of their final structures. Within this dissertation, mobile builders are defined as distributed bespoke robots distributing continuous materials that will not expected to be reconfigured later[90]. The criticism of discrete materials often stems from two main factors: their module-oriented design and weak connections between modules. This aspect of mobile builders can overcome by use of continuous materials. Like mobile assemblers, they mostly operate aerially or terrestrially in a form of drones or riding/climbing robots and their main goal is to perform over larger spaces than conventional machines or industrial arms[240]. Mobile builders can also be understood as a discretization of conventional machines (e.g., 3D printers, robotic arms, CNC systems) into mobile collaborative components[90].

4.3.1 Described mobile builders

Even mobile builders are not working with discrete(modular) elements or materials[56] the few recent developments selected just provide an overview within distributed systems. This section does not discuss constructional robots, described by in detail by Bock in *Constructional Robotics* [251]. The robots selected for discussion below were designed to be cooperative and to be employed in architectural applications.

4.3.1.1 Minibuilders

“Minibuilders” were developed as a reaction to the space limitations of large-scale 3D printing in 2014[252]. The continuous material in this system which was concrete 3D printed by means of controlled distribution by mobile builders. The Minibuilders system consisted of a group of different robotic typologies with varying tasks for the building process including a base robot, a grip robot, and a vacuum robot[252]. The base robot deposited the first ten layers of concrete. The grip robot was fundamental for the entire system and was equipped with a climbing mechanism as well as a printing head. This robot climbed on the structure which was 3D printed by itself. The vacuum robot deposited additional materials on the surface of the printed shell, enhancing its structural properties. The Minibuilder system provides an excellent example of how volume-limited fabrication methods could be replaced with mobile bespoke robots in which certain tasks are distributed through different types of robots toward the one goal. This is similar to the behaviour of social wasps, bees, or ants who also collectively distribute work over members with different functions (see Section 3.2.2).

4.3.1.2 MoRFES_01

MoRFES_01 was developed in 2018 [90]. Like the Minibuilders system, the MoRFES_01 system combined different types of robots in order to overcome the spatial limitations of standard machines—in this case, the limitations of industrial arms in terms of distributing fibre threads. Two types of bespoke robots were used: a “sheet climber” and a “thread walker.”[103] By means of cooperation, a final tensile thread structure as wound between two sheets. The climbers defined the positions of the thread anchor points and the walkers carried threads in-between the climbers. A similar technique was used for the ICD/ITKE research pavilion 2017 [240]. For the pavilion, drones were used to carry carbon and glass fibres in cooperation with an industrial robot. The fibre materials included tensile structures, and fibre composites provided high tensile structural performance with an ultralight design. New, lighter materials open up new options for use of robots, which can be smaller with lower payloads.

4.3.1.3 Fiberbots

The “Fiberbots” system was developed in 2018 [97]. The system mimicked flocking, a boids swarm behaviour (Section 3.2.2). Sixteen bespoke robots tailored 4.5 m tall pipe-like structures using a glass fibre composite. The mobile robots had three main functions: climbing, fibre-filament winding, and UV curing. The robots climbed inside an already-fabricated pipe. An endless glass fibre filament was wound around the robot, which worked as a mould[97]. The robot was equipped with UV light used for resin curing. The winding robot was stabilized by the pressure of a pneumatic pillow to the wall. This step also defined the direction of a pipe. Fiberbots represent a combination of the previous two examples in which a fibre filament was deposited using a 3D printing-like process. Unlike the previous examples, Fiberbots essentially packed several technologies into one compact device.

4.3.2 Mobile Builders: Summary

Mobile builders are specific category within distributed robotic systems. Compared to other types of systems (mobile assemblers and modular builders), these systems do not deal with discrete assembly. Their fabrication is more or less continuous, but the overall "end product" (e.g., a 3D printed structure, the deposit of fibre) is distributed within the devices used to achieve broader goals (for example, larger volumes, faster fabrication times, ability to reach more places or to distribute weight). Mobile builders should work hand-in-hand with new materials. To maximize the potential of employing mobile builders in architectural applications, three main aspects should be considered in symbiosis in order to move towards a complex sustainable construction process: material performance, design independence, and fabrication.

4.3.2.1 Material performance

New technologies should work hand-in-hand with new materials and any new process should provide a complex solution that does not simply replace humans with robots. Materials play significant roles and define the specifications of robot, and vice versa. Recommended materials for future use in architecture include lightweight materials, precise materials, strong materials, dry materials—and eventually deployable and flexible materials.

4.3.2.2 Design independence:

The range of possible design outcomes should be as versatile as possible. Architecture requires diversity of shapes, typologies, colours, and so on. A system should also work in different environments.

4.3.2.3 Fabrication

Fabrication mechanisms should be selected with an eye towards building specifications. The specifications for materials used should not negatively influence functionality or require special maintenance such as cleaning.

4.4 Summary: Distributed robot systems

All three types of robot systems are still the focus of research investigation and their use in architectural applications, especially in case of modular robots, is still in its infancy. Mobile assemblers and builders have already been applied and successfully tested on small architectural projects[90], [97], [252]. To work with such systems requires a complete re-thinking about how architecture functions. A final design should ideally follow fabrication and material possibilities (and not the other way around). The task for architects is to find the optimal balance between robotic complexity and the universality of solutions. Important question revolves around the integration of continuous processes within discrete reconfigurable buildings. The combination of discrete and continuous fabrication methods can result in a conflict in which continuous parts block the reconfigurability of discrete elements[96].

The three types of systems highlighted showed different approaches that, in combination, can result in functional systems. In an extremely optimistic future scenario, modular robots would be able to substitute for both the other types if it is considered that modular robot can transform to various machines(eventually materials) includes also mobile builders and assemblers. However, such systems still need many years of research before large-scale implementation in architecture is imaginable.

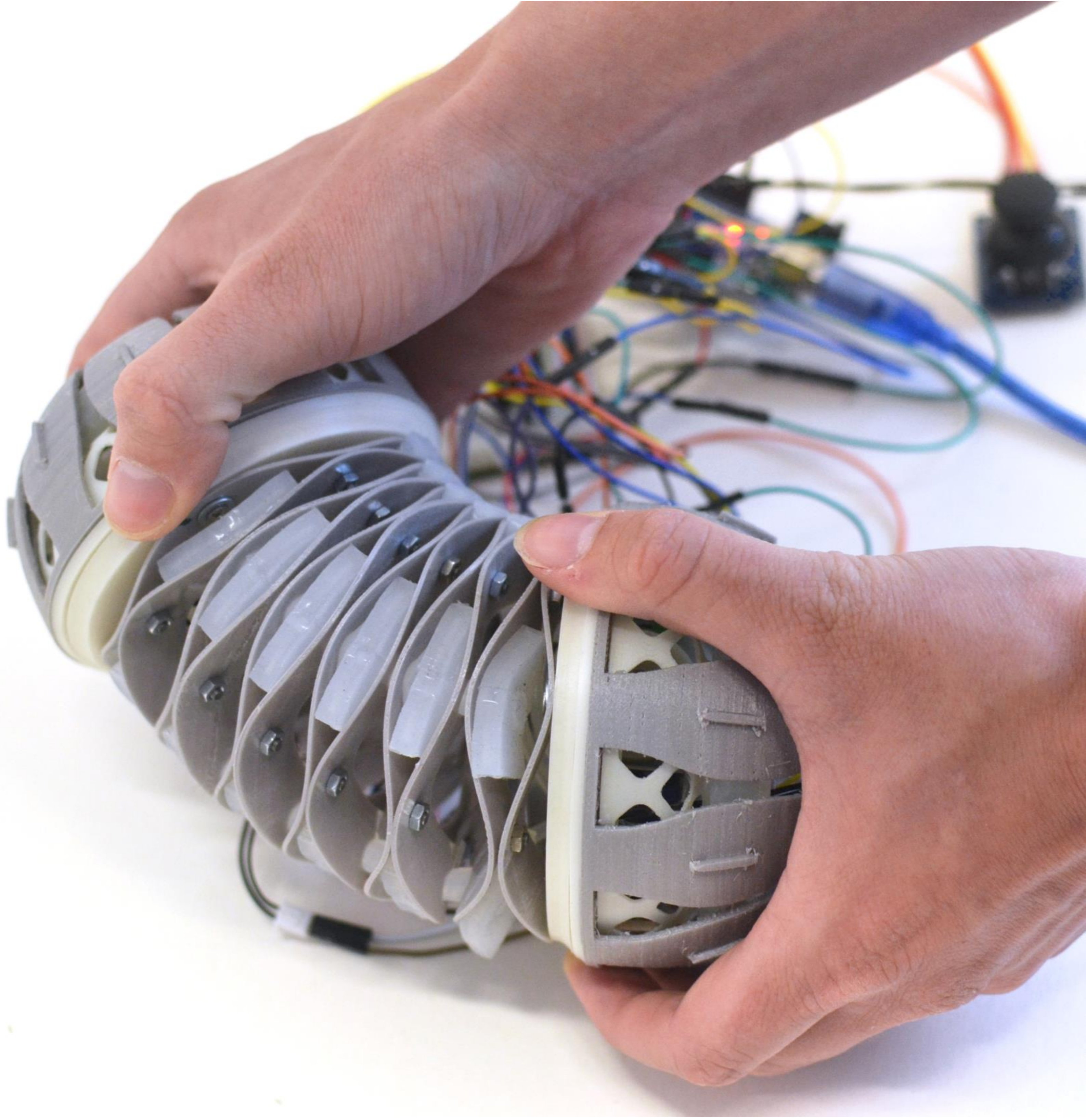


Fig. 30. Soft sharable robot for MoleMOD Version 1

Chapter 5.

SOFT ROBOTICS

Ever since architecture introduced reconfigurable and kinetic systems to its discourse, discussion about actuators have risen in numbers. Heavy mechanisms, with their origins in the Industrial Age, are ill-suited to building environments which require flexibility, lightweight, and safe. This gap triggered interest in the development of soft actuators based on the compliance of lightweight materials. The topic of soft robotics [253] is currently being discussed as an alternative to traditional mechanical robots [57], [112]. The author of this dissertation investigated different shapes and configurations of pneumatic soft-fluidic actuators (PFEA) towards development of the soft body of “Mole” (sharable actuator of MoleMOD) described in Section 7.2.4. In fact, the author examined soft actuators throughout the process of researching this dissertation as a crucial technology for the movements of sharable actuators.

Soft robotics is rapidly growing field of robotics that has to date had influence mainly in medicine and in the development of robotic gripping systems. Few investigations have been devoted to mobile robotics [244]. Soft robotics is following the trend of modern technologies to be smaller, lighter, faster, and softer than ever before, while energy consumption is minimized and overall weight is reduced[254]. Ever since the first soft robotic gripper was introduced [255], architects have found soft robotics to be an alternative technology to frequently used heavy mechanisms in reconfigurable and kinetics architectural systems. Most of these robots consist of hard parts from materials like steel or plastic powered by complex mechanisms like gears, motors, and so on. These human-made mechanisms have capabilities far beyond natural mechanisms which are mostly based for soft movements using muscles and tissues [256]. Softness is the main feature of materials for soft robots/actuators. Soft actuators are perfect for unknown and complex environments and are capable of particular replacing of sensors and highly precise expensive hard actuators.

Within the field of soft robotics, two terms are primarily used: Soft actuator and soft robot.

- *Soft actuator*

An actuator is a fundamental technology that provides motion. Most hard actuators are based on hydraulics, pneumatics, or electromagnetics which powers cylinders, motors, valves, and so on. Soft actuators are solely used for simple movements (e.g., twisting, bending) through the novel characteristics of the soft materials employed. Typically, a soft actuator is part of a soft robot or a soft actuated kinetic system.

- *Soft robot*

A soft robot is a kind of end product that includes soft actuators. Soft robots are designed for specific tasks such as walking, swimming, manipulating, or protecting and they have specific shapes and predefined movements, mostly following natural inspiration[244].

The goal of the author's ongoing research is to reach maximum adaptivity (flexibility) with high precision and controllability. Achieving these goals is a challenging task, because increasing adaptivity (flexibility) of materials typically decreases precision and controllability. A key aspect is the selection of the material used in the soft actuators for particular applications. Applications should primarily focus on adaptivity, flexibility, and safety—high precision should not be the main focus.

5.1 Materials of soft actuators

In soft actuators, forces are transformed through soft materials (e.g., silicon rubber, electroactive polymers, gels, carbon nanotubes) which provide certain soft movements. The materials are activated by distribution of fluids, electromagnetic forces, temperature change, moisture, and so on. Materials used usually have a Young's Modulus in range of soft biological materials ($<10^4$-10^9 Pa) [257]. Such actuators accomplish tasks through adaptivity, safety, and flexibility—usually accompanied by lightness [254]. The material defines properties such as the weight, cost, and energy consumption of a complete actuator/robot. Most of the systems use one or two materials, which performs by their specific shapes and configurations. The distribution of materials over an actuator defines its deformation and, by the programmable deformation, goal performance is achieved[258]. The softness of actuators is divided into extrinsic and intrinsic kinds. ”Intrinsic softness” is achieved from the material characteristic (Young's Modulus) of the main composing material (Fig. 31). ”Extrinsic softness” refers to increased compliancy of the actuator through its mechanism design (i.e., springs, compliant joints) [259]. Hybrid actuators fall somewhere in-between. Most soft robots are actually hybrids, because they often use constructional rigid parts.

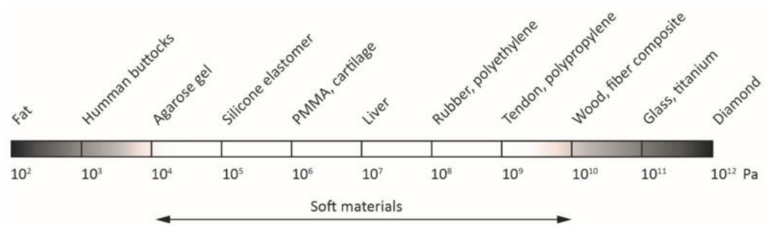


Fig. 31. Young's Modulus of different materials mostly for soft actuators. Adopted from [257]

Ever since soft actuators were introduced, several material combinations and methods have been developed and these can be categorised and qualitatively described into five main groups regarding their use in small-scale robotics: Fluidic elastomeric actuators (FEA), Shape memory alloys (SMA), Shape memory polymers (SMP), Electroactive polymers (EAP), and Magnetic actuators (MA)

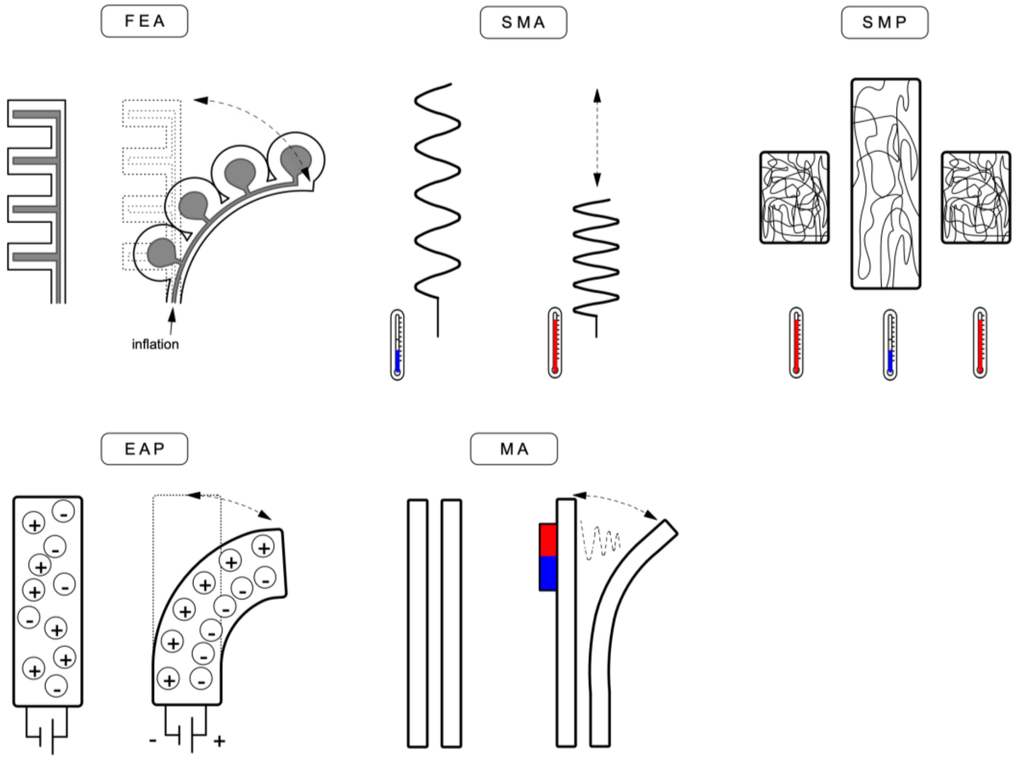


Fig. 32. The five basic types of soft actuators: Fluidic elastomeric actuators (FEA), Shape memory alloys (SMA), Shape memory polymers (SMP), Electroactive polymers (EAP), Magnetic actuators (MA).

5.1.1 Fluidic elastomeric actuators (FEA)

Fluidic elastomeric actuators are the most commonly used soft actuators, mostly because they are made of easily accessible materials and are simple to manufacture. FEA uses a compression or vacuum when air (pneumatic fluidic elastomeric actuators [PFEA)]) or different liquids (hydraulic fluidic elastomeric actuators [HFEA]) deform an actuator by contact with the inner surface of the chambers of an actuator[260]. To achieve controlled deformation of an actuator, the design of inner chambers and/or reinforcement pattern must be considered. FEA uses principles similar to hydraulic or pneumatic cylinders in which fluids changing their surrounding shapes. The difference lies in the materials used that, through their softness, deform in all directions (not only in one direction as with cylinders). Multi-directional deformation has an infinite number of degrees of freedom depending on the elasticity and compliancy of materials used, the geometry of chambers, reinforcement mechanisms, and programmed thickness of materials. FEA actuators are the most advanced of all the actuators, and some of them have even found industrial applications[261]. The advantage when compared to other types of actuators is higher displacement and power. The disadvantage of this kind of actuator is their need for external devices like pumps and valves (pumps influence the power of an actuator and the time needed for displacement while valves control the distribution of fluids in an actuator[110]). Often these devices are not presented as part of a soft robot/actuator but are, rather, hidden behind the scenes. If considered part of an overall soft system they make a whole technology implementation hard and heavy. This is the reason why researchers have been developing soft actuators based on electromagnetic or temperature stimuli that do not require heavy and rigid power supplies[19] [261].

Pneumatic fluidic elastomeric actuators (FPEA) are used for MoleMOD. They were also used for the Interactive Soft Actuated Environment workshop designed and organized by the author together with Vasilija Abramovic at CTU Prague in 2019. During the workshop, students tested three types of FPEA: an origami soft actuator [262], a 3D printed actuator [119], and a Mc Kibben actuator [263] shown in Figure 33.

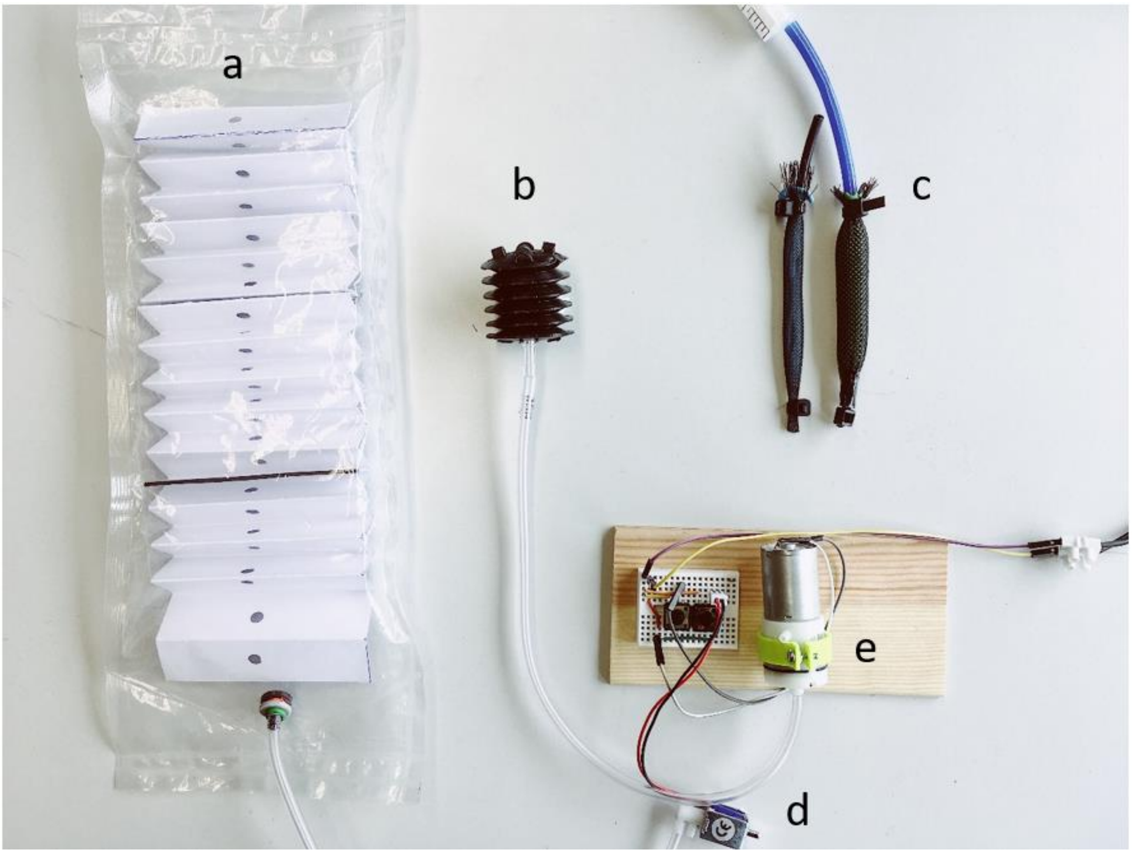


Fig. 33. Set of three different actuators: (a) Origami actuator, (b) 3D printed actuator, (c) Mc Kibben actuator, (d) Solenoid valve, and (e) Mini Air Pump.

5.1.2 Shape memory alloys (SMA)

SMA are alloys with the ability to return to their original shapes after they are deformed, so-called “martensitic/austenitic transitions” [260]. Shaping to an original state happens when the alloys are heated. For soft actuators, a metal alloy consisting of nickel and titanium is used most often (NiTi, so-called “Nitinol”) [264]. Programmed deformation is achieved by the different thermal expansivities of materials used (typically two) composed in layers. Deformation is controlled by deposition of both materials over the actuator and by heating/cooling, they usually bend, shrink, or elongate. The displacement is insignificant compared to FEA; to overcome this problem, the shape of an SMA is usually formed into a spring or into meandering profiles that increase displacement [260]. SMAs do not have the same power as FEAs and their utility lies mainly in performing self-weight. The greatest advantage is their lack of heavy interior devices such as motors or pumps. Deformation through heating can happen passively by harnessing the surround temperature or by actively heating up an SMA using an electric current. Disadvantages of SMAs include low power and poor controllability of heat over the actuator. If current is used, substantial energy losses must be considered. An SMA actuator (Flexinol ® from DYNALLOY, Inc., Irvine, U.S.) was tested by the author as an alternative to FEA for the soft body of the sharable actuator used in the MoleMOD system (Fig 34). However, because of its low power and poor controllability accompanied by minimum displacement, it was not additionally investigated.

Fig. 34. Testing of Flexinol ® for Mole soft body within the MoleMOD system.

5.1.3 Shape memory polymers (SMP)

SMPs work similar to SMAs, though with external stimuli they have the ability to return to their original phases [265]. SMPs are deformed by melting and glass transition as they change their shapes from rigid to soft phases. Compared to SMAs, their greatest advantages in terms of implementation is in their displacement (up to 800%), lower prices, and material densities. Disadvantages include complex manufacturing processes and one-way actuation [260]. SMPs are typically conducted by heat or electromagnetic fields. Several experiments use polymer transition light [266] or liquid solutions [267]. They can be used like SMAs when focus is on lightweight investigations with minimum payloads.

5.1.4 Electroactive polymers (EAP)

EAPs are responsive smart materials stimulated when an electric field is applied to them. Material performance and shape configurations are, within types of soft actuators, closer to SMPs or SMAs than FEA. But, unlike them, electricity deforms the polymer by means of electrostatic forces, not heating of the polymer as in the case of SMAs and SMPs. Two main types of EAPs exist, according to number of publications: the larger group, Dielectric Electroactive Polymers (DEAP); and smaller group, Ionic Electroactive Polymers (IEAP) [18]. Both can be used as soft actuators as well as soft sensors [268].

5.1.4.1 Dielectric Electroactive Polymers (DEAP)

DEAPs are actuated by electrostatic forces [269]. Their sandwich layout consists of elastomeric film squeezed by electrostatic forces between two electrodes on each side of the film. Performance is based on physical effects: when high voltage is applied, electrostatic pressure expands the polymer film, which leads to displacement of the overall actuator [18]. DEAPs operate under high voltage (several kilovolts), which makes them potentially dangerous to humans. The high voltage can also damage an actuator. On the other hand, compared to IEAPs, which work at lower voltage levels, DEAPs are better investigated, more controllable, and stronger than IEAPs.

5.1.4.2 Ionic Electroactive Polymers (IEAP)

IEAPs are based on the transition of ions between a bi- or tri-layer setup based on electrochemical transition [18]. For activation, significantly lower voltage is applied (<3V) compared to IEAPs. This makes them more attractive for applications where human/actuator interactivity is expected. IEAPs are not as developed compared to DEAPs and, as a result, are less controllable [18].

5.1.5 Magnetic/electromagnetic Actuators (MA/EMA)

MA/EMA actuators mostly consist of ferromagnetic particles disposed in polymeric or metal substances deformed by external electromagnetic forces [270]. By controlled distribution of particles in a substance, the programmed deformation of this type of actuator is achieved [270].

5.2 Design Of Soft Robots

The excellent adaptivity, safety, and flexibility of soft actuators triggered the author of this dissertation's interest in investigating them for specific performances, primarily, mimicking the movements of living organisms. Most typical applications rely on gripping systems. Within architecture, soft actuators have found applicability for reconfigurable façades and interactive installations [271][17]. For this dissertation, the most relevant applications are in the creation of mobile and modular robots and, to a certain extent, gripping systems.

The different behaviours and designs of soft robots can be divided into five groups: manipulating, mobile, modular, foldable, and wearable robots.

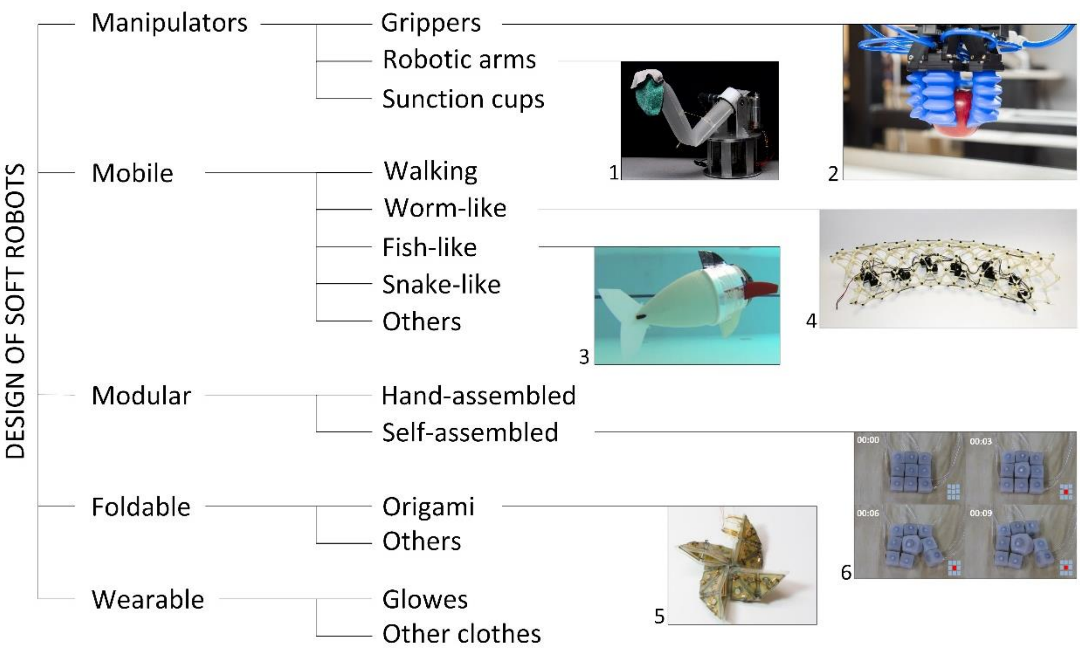


Fig. 35. Design of soft robots: (1.) Soft inflatable robot arm [272], (2.) Soft robotics gripper [273], (3.) Soft robotics fish [274], (4.) Meshworm [264], (5.) JAiMY soft origami robot [275], and (6.) Soft modular robotic cubes [276],

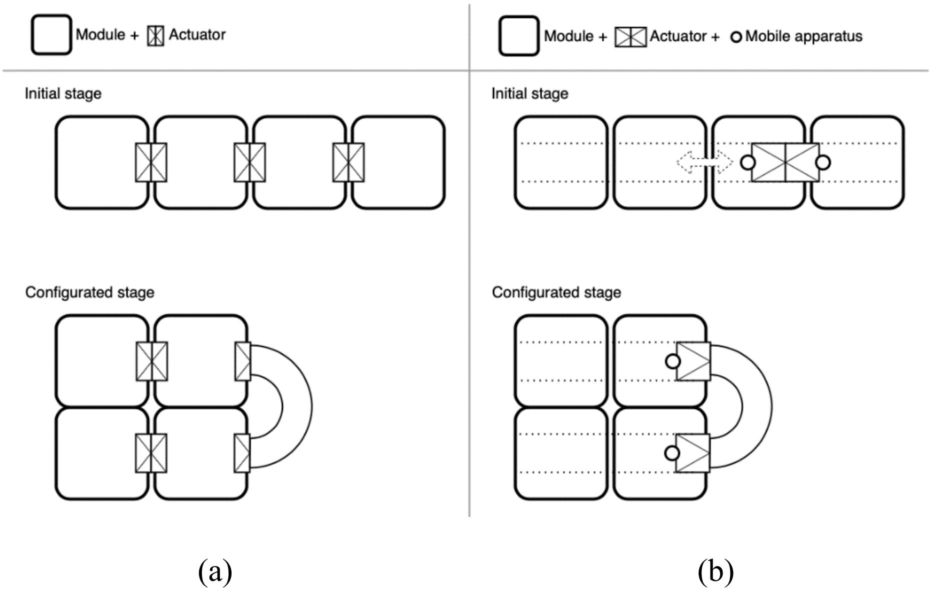
For the scope of this dissertation, the most relevant development is PFEA, used for the development of the sharable actuator in the MoleMOD system. Even though PFEA requires heavy devices (pumps, valves) accompanied by tubing and connections, its performance was significantly better than other actuators (SMA, SMP, EAP, MA) tested. Achievable lifting force was essential for robot manipulations for this research project and other important aspects are: price of the actuators, large displacement, density of materials, and robustness. Disadvantages lie at the point of fabrication, when leakage must be avoided. This can be difficult without professional tools.

Fig. 36. Self-reconfigurable robotic system with sharable actuators / MoleMOD Version 5

Chapter 6.

SELF-RECONFIGURABLE ROBOTIC SYSTEM WITH SHARABLE ACTUATORS

The novel concept of a modular robot for use in architecture was first introduced by the author in 2017 [109]. It was primarily a reaction to the extremely high overall price of modular reconfigurable robots, which is not feasible for applications requiring high numbers of modules. Such applications include architecture, the area in which the system was primarily focused. High prices are directly influenced by the cost of the consumable mechatronic parts that are typically part of every module within self-reconfigurable robots. To overcome this general problem, the author introduced a reconfigurable modular robot in which actuators are exchangeable (i.e., sharable) between modules. Within many prior studies, this concept attracted interest because the reduction of cost is a crucial issue[277]. Many researchers view such systems as kinds of mobile assemblers, primarily because their focus is solely on the movement of sharable actuators between modules. Upon closer observation, the overall behaviour of such systems more closely resembles that of modular robots, mostly because of typical characteristics for modular robots such as reconfiguration with the assistance of a neighbouring module, accommodation of active parts inside of a module, and active connections. Indeed, self-reconfigurable robotic systems with sharable actuators can be seen as hybrids of mobile and modular robots, with their robotic modular systems equipped with actuators that function as a mobile apparatus shared among modules (Fig. 37).



(a) (b)

Fig. 37. Simplified comparison between a reconfigurable modular robot (a) and a reconfigurable modular robot with a sharable actuator (b).

The novel concept developed in 2017 and presented here works with various configurations, materials, and geometries. The significant step towards cost reduction was the separation of the active part (robot/actuator) and the passive part (module) of the system. For successful implementations, these parts should be designed in symbiosis and ideally influence one another. During experimentation, this was critical for developing functioning prototypes. Sharing of actuators have many special characteristics that have not yet been investigated by researchers testing reconfigurable modular systems. Thus, it is important to observe their performance with physical testing.

To address all the pros and cons of this concept, this section is divided into several paragraphs illustrated by a diagram that explains roles within the distributed systems (Fig. 38).

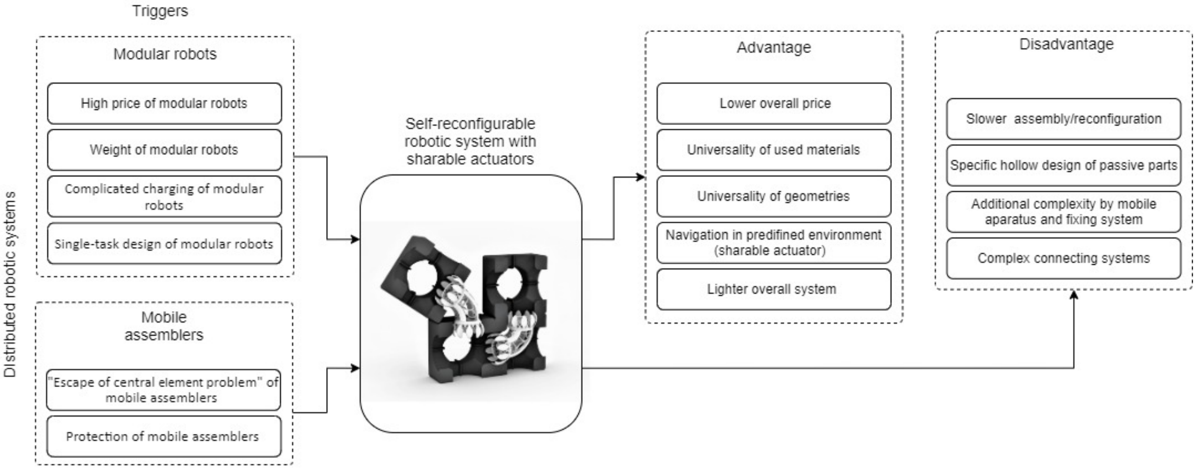


Fig. 38. Diagram illustrating the role of a reconfigurable modular robot with sharable actuator within the distributed robotic system. At left, triggers impacting distributed robotic systems. At right, advantages and disadvantages of such systems.

6.1 Triggers impacting distributed robotic systems

6.1.1 High price of modular robots

The high price of modular robots stem mostly from the high price of mechatronic active parts (defined as actuators). For this reason, the author recommends sharing the actuators between modules (modules are, in both cases, considered to be passive) instead of having them permanently fixed within every module. To make the concept work, the sharable actuator must be equipped with a mobile apparatus. To address the concept, a basic price derivation for both systems was determined. The price of most of reconfigurable modular robot systems (P_{mr}) is defined by the cost of a module (C_m), and the cost of an actuator

(C_a), while both are multiplied by the number of modules *(N_m)* (Equation 1). The price of a reconfigurable system with a sharable actuator *(P_{ms})* is defined as the costs of a module *(C_m)* multiplied by the number of modules *(N_m)* plus the costs of soft actuators, where each is defined by the costs of actuator *(C_a)* plus double the costs of the mobile apparatus *(C_{ma})* (Equation 2). For modular robots with sharable actuators, the effective minimum number of modules *(N_m)* must be determined (Equation 3). The main influence is the ratio between the costs of the mobile apparatus *(C_{ma})* and the actuator *(C_a)*. For the calculated sharable actuator, there are always two mobile apparatuses on both sides of an actuator, as ascertained during the experiments. Different numbers of mobile apparatuses can be counted.

$$(1)\ P_{mr} = N_m \times C_m + (N_m - 1) \times C_a$$

$$(2)\ P_{ms} = N_m \times C_m + N_{sa} \times (C_a + 2 \times C_{ma})$$

$$(3)\ N_m \geq 1 + N_{sa} + 2\frac{C_{ma}}{C_a}$$

These are basic equations that should be considered before the start of a project. Different aspects related to a more detailed feasibility study such as energy consumption of the mobile apparatus, maintenance, and software costs should be addressed after detailed planning of the system itself, in the experience of the author.

6.1.2 Weight of modular robots

Weight is a crucial aspect for all kinetic, mobile, and robotic systems. The general goal is to reduce the weight of components to minimize energy, payload, torque, cost, and material consumption required for an implementation. Reduction of heavy electronics in reconfigurable modular robots allows smaller actuators with lower energy consumption to be used. The derivation of the effective number of modules, according the weight, follows the same principles as for price, with costs *(C)* and price *(P)* being replaced by weight *(W)*.

$$(4)\ W_{mr} = N_m \times W_m + (N_m - 1) \times W_a$$

$$(5)\ W_{ms} = N_m \times W_m + N_{sa} \times (W_a + 2 \times W_{ma})$$

$$(6)\ W_m \geq 1 + N_{sa} + 2\frac{W_{ma}}{W_a}$$

6.1.3 Charging of modular robots

Considering charging is crucial for overall long-term functioning. The question of how modules are charged when they run out of battery power must be addressed.

- Optimally, there would be a constant distribution of energy over a system. On the other hand, this is extremely complicated and presents limitations to possible assembly configurations.
- Another option is to reconfigure a module into a charger when a battery runs down. This option is more feasible than the aforementioned option. However, this option introduces its own challenges: the distribution of global performance is impacted by movement towards a charger, and the control system becomes more complex.
- A final option is an external device operating over the structure and exchanging or charging batteries.

Charging issues are not so crucial for chain modular robots because they can be constantly connected to a power supply at one of their ends and energy is distributed through the whole length of the chain of modules. By sharing actuators, charging can easily be achieved because the actuators can simply move to a charger guided through the modules. Another advantage of this configuration is that the modules in passive mode are not connected to a battery. This extends the lifetime of a battery.

6.1.4 Single task design for modular robots

Modular robots are primarily designed only for one task: reconfiguration. This task is determined by the kind of technology used, usually fixed permanently to a module. With a fixed shape and material, other functions such as transparency, softness, insulation, energy absorption, and so on are not possible. According to the sharing concept, the materiality and shape of a building element (module) is partly independent of its mechanical parts. This is important for architects, who typically deal with choices regarding a range of materials, shapes, and colours.

Because modular reconfigurable robots with sharable actuators are comparable to mobile assemblers, two main aspects regarding them must be addressed, as discussed directly below.

6.1.5 “Escape of central elements problem”

The problem of limits to reconfigurability stems from the manipulating space available to a mobile assembler. The “escape of central elements problem” is in detail described in Section 4.2.1.

6.1.6 Protection of mobile assemblers

Most mobile assemblers operate on the outer surface of assembled modules. This puts them in contact with their surrounding environment. Weather conditions, humans, and animals can come into contact with such a robot, so the robot should not injure humans or animals, and potential weather damage should be considered. In the case of sharable actuators, movement takes place inside of protective modules and the active part is not in contact with the surrounding environment.

6.2 Summary

In this section, key aspects defining the development of modular robots with sharable actuators were discussed. The positive features of modular robots lead to a reduction of price and weight, but several specific features must be considered. A sharable actuator needs a manipulating space in real world implementations. This determines specific design of a system, and inside each module should be a channel for operation. Specific movements also determine the overall behaviour of reconfiguration, which is complex. Such systems are designed for slow reconfigurations because a smaller number of actuators than modules means any overall reconfiguration takes time. Hence, modules cannot be transformed in parallel and time for movement of the robot between manipulated modules is needed. This “speed of assembly” can be controlled by the number of active parts in a system, and a system will reach its maximum speed when one actuator is in every module. Regarding the control and sensing, the navigation strategy for such robots is quite advantageous because the robots move in a predefined environment by means of modules. Such movement of the robot (sharable actuator) can be discretized based on the positions of modules, and each movement of the robot can be optionally pretested and tuned. When robots move in known environments consisting of highly specified discrete components, the number of sensors required can be reduced compared to motion through real world environments [250].

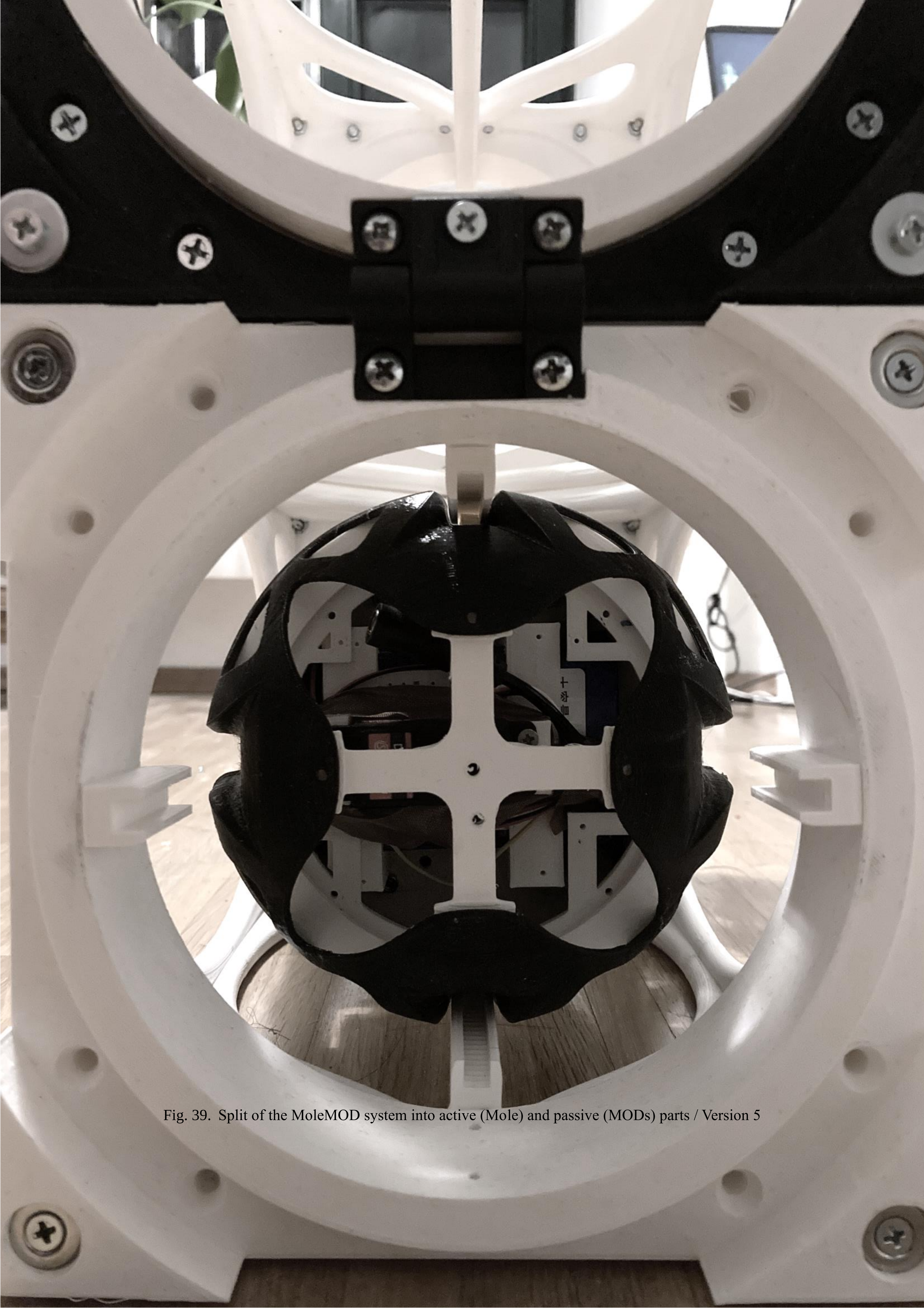


Fig. 39. Split of the MoleMOD system into active (Mole) and passive (MODs) parts / Version 5

Chapter 7.

EXPERIMENTS

To prove the concept of a self-reconfigurable robot with a sharable actuator, several prototypes and tests were conducted by the author with the reconfigurable system "MoleMOD".

This chapter is divided into the three main parts: an introduction to the world of MoleMOD, MoleMOD ingredients, and a summary.

- *Introduction to the world of MoleMOD*

This section introduces the overall "MoleMOD" concept. It describes the diversification of six versions of MoleMOD that have been developed by the author since the idea was first introduced in 2016 [109]. The focus is mainly on the active part of the system and design aspects of MoleMOD iterations are also discussed.

- *MoleMOD ingredients*

This section describes all the specifications for MoleMOD and their testing regime. This section is divided first into active and passive parts of the system and then provides a description of detailed specifications such as robot components, materials used in the passive system, joints, simulations, and parametric models.

- *Summary*

The final section summarizes all types of robots created and compare them based on specifications from the "ingredients" section.

7.1 Introduction to the world of MoleMOD

MoleMOD extend the current range of modular robots with a new approach characterized by a split of the modular robot into active and passive parts according to the novel concept of creating a self-reconfigurable robot with a sharable actuator as discussed in Chapter 6. This split provided the name to the entire system: "MoleMOD" is a combination of "Mole" (representing the active part) and "MOD", which represents the passive modules.

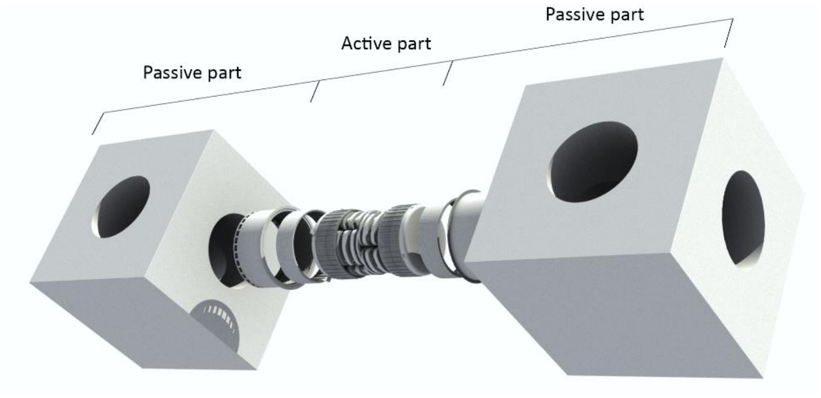


Fig. 40. Split of the MoleMOD system into active (Mole) and passive (MODs) parts.

Mole

This is an active part shared between passive modules (MODs). It has two main functions: mobility and reconfigurability. These details are described further in Section 7.2.4.

MOD

is the passive part (module), which is the building unit (material). MODs are formed into a discrete structure with interior channels which guide the robots.

Six versions of MoleMOD were created, and they can be separated into the two groups. The first group employed a lattice-based architecture (versions 0-3a), and the second group used a chain architecture (versions 3b-5). Another significant change was in the type of movement for Mole. Versions 1-3 only investigated peristaltic motion [264] through soft pillows, and versions 4-5 used cogwheels together with cog tracks.

7.1.1 Version 0

The first version of MoleMOD defined the future development of versions to come. Some specific components and principles remained until the last, fifth version was created. This version was called “version 0” because it was used mainly in order to gain a basic understanding how it worked with soft materials, including their control. Even though it was a kind of testing version, the general design remained the same in later versions: the active part (Mole) consisted of two heads navigated in five directions by a soft/flexible body. The body consisted of four bellows that defined the direction of bending and expansion and contraction of the body itself. Version 0 already used mini air pumps and solenoid valves for air distribution into the bellows. Compared to the other versions, higher focus was given to connections between passive parts. The goal was to have a genderless connection in which the modules (MODs) were screwed together by mechanisms in a sharable actuator. This influenced the head of Mole, which was equipped by *revolving casing*. Version 0 considered peristaltic types of motion between modules by sequential fixing of the robot into the surface of a channel using of latches. Version 0 did not fully test manipulation with MODs nor did it test peristaltic motion. The main concern was, rather, on development of the soft body and its control. Highly problematic areas of Version 0 included silicone pillows in combination with rigid polylactic acid (PLA) vertebras that were not very adaptive and hard to control (Fig. 41).

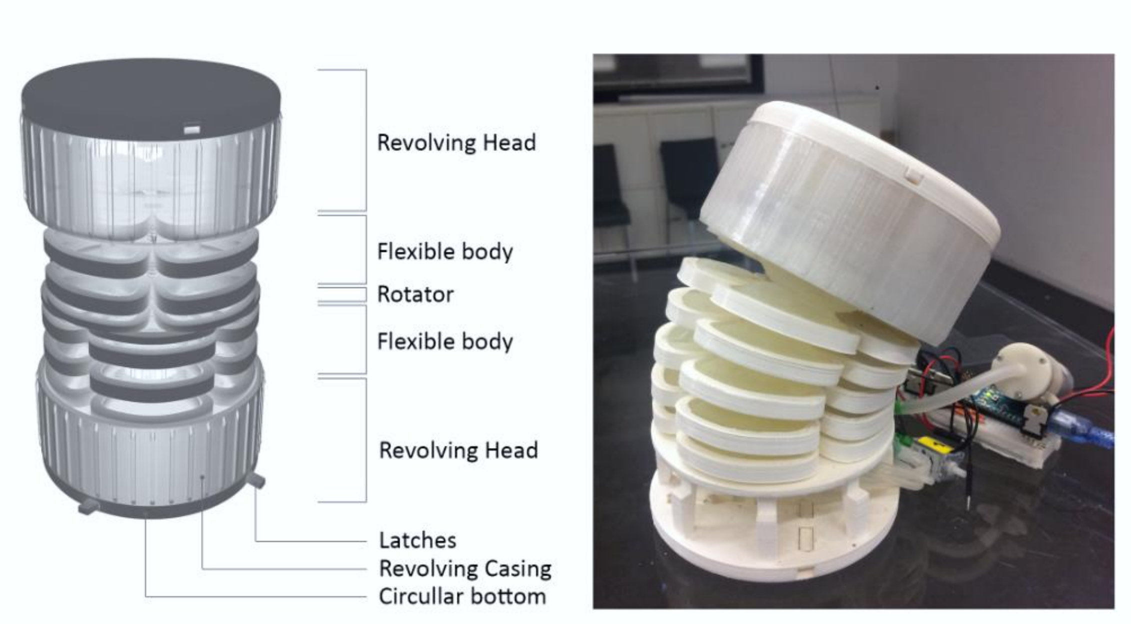


Fig. 41. Mole Version 0.

7.1.2 Version 1

Version 1 mainly explored the active part of the robot, which became softer than in Version 0. The body was designed as a fully soft hybrid of silicone pillows placed between thermoplastic polyurethane (TPU) layers connected to wave springs. The head was soft, with fixation latches replaced by inflatable fixing pillows and with revolving casings replaced with more elegant leaf shaped, flexible, TPU casing. The passive part was no longer considered to be a cubic shape as in Version 0, but cylindrical and branching shapes were also tested. The second version of Version 1 was able to control and bend its soft body into all four directions (Fig. 40-41). Unfortunately, the silicone material used for inflatable pillows in the soft body was not strong enough to move with the passive parts. This was the last version in which silicone was used for any component in Mole, not only mechanical reasons, but the fabrication of silicone was found to be inappropriate and time consuming as well.

Fig. 42. Mole Version 1 and its bending in all four directions.

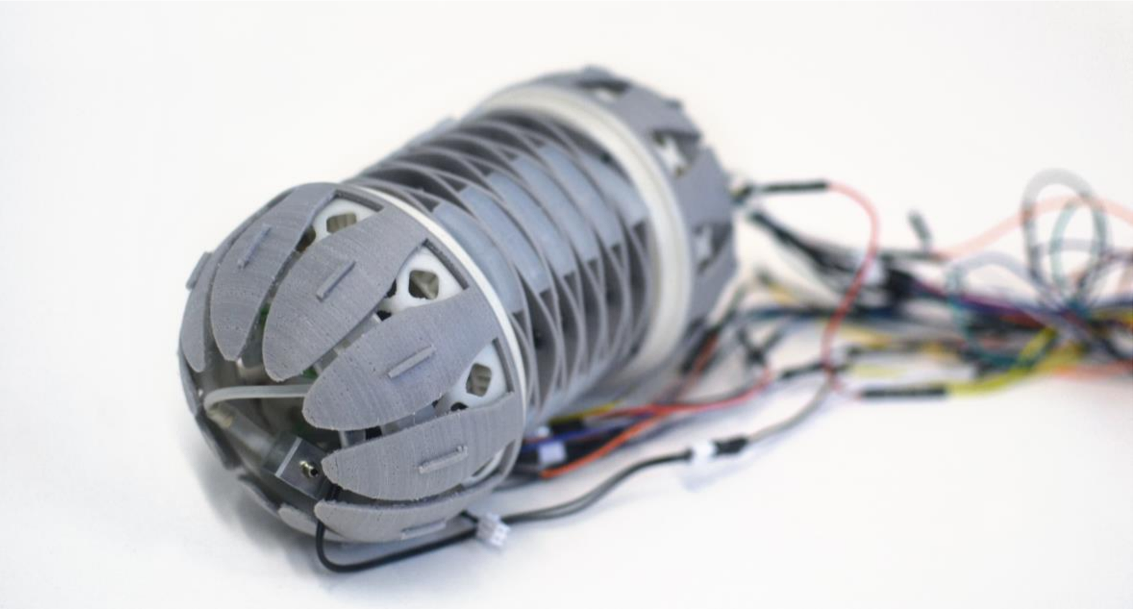


Fig. 43. Mole Version 1.

7.1.3 Version 2

Version 2 investigated only the active parts (Mole parts). Based on previous versions, its main task was to achieve stability, higher control of the soft body, and greater ease in fabrication. The goal was use standardized components that could be replaced when damaged. Due to practical reasons, Version 2 had larger diameter (145 mm) than the previous version in order to accommodate all piping and electronics in both heads.

The soft body consisted, as in Versions 0 and 1, of a hybrid wave spring with integrated pillows. Harder Poly(methyl methacrylate, PMMA) material was laser cut to produce these. Compared to the previous silicone or TPU versions, PMMA stores more energy that is elastic. The stored energy works in a longitudinal direction opposite to the direction of inflation. Silicone pillows were replaced by hybrid pillows consisting of latex balloons and a TPU cover. The cover protected inflation against uncontrollable hyper-elastic expansion. Soft body precision was supported by neodymium magnets that helped return Version 2 into its original "spring state" after inflation. Version 2a was designed to test the controllability and stability of a soft body and thus, revolving of the head and screwing of modules together were avoided. The head was used only to fix the robot in a goal state by means of inflation of the continuous hybrid of latex and a TPU pillow. The pillow was placed between the inner part of the head and an outer flexible casing

The third version of Version 3, as with its first iteration, conducted a simple peristaltic movement inside a transparent PMMA tube used for testing and it was able to move together with lightweight passive elements made of polystyrene. Even though this version was more stable than the previous version, the spring was not stronger than the weight of the MODs carried together with the head of the robot. This led to collapse when the structure was not supported by air since the robot was fully dependent on the stiffness of the spring. Another problem was a small extension in longitudinal direction that could not achieve effective peristaltic movement nor a 90-degree bending angle. It was clear that the combination of a compliant spring and inflatable pillows would be not the best solution, especially because in conception, the ideal MoleMOD requires both high extension and stiffness.

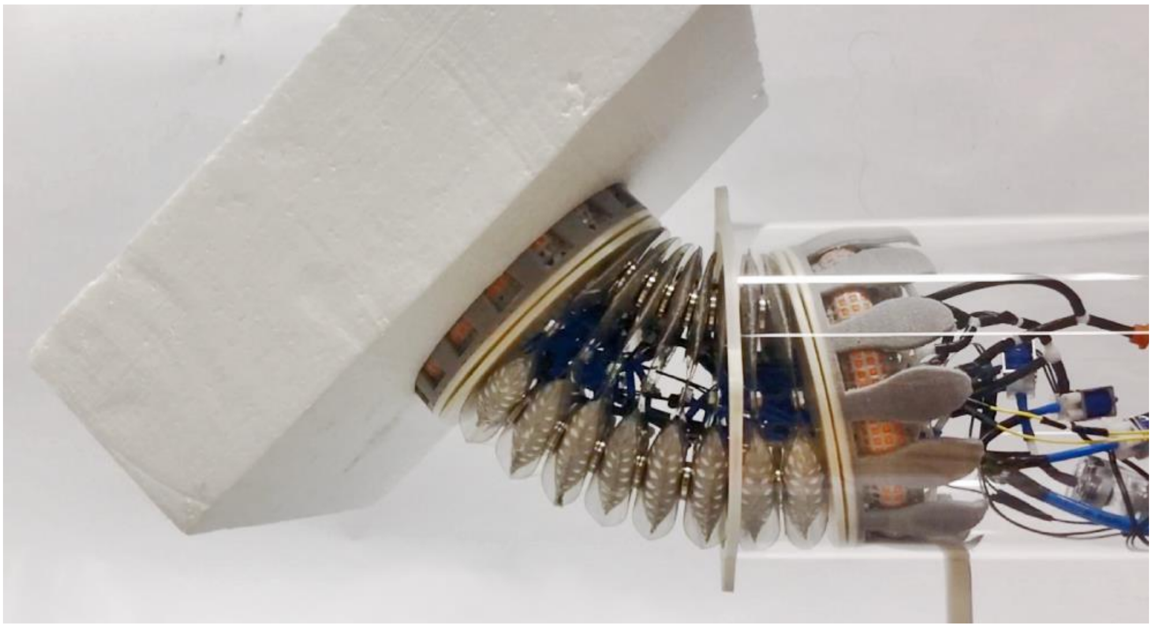


Fig. 44. Manipulation with segment of passive part by Mole Version 2.

7.1.4 Version 3

Version 3 was most revolutionary version of all versions created in terms of its active and passive parts. The active part began to combine compression and a vacuum for better controllability and stiffness. The geometry and assembly plan of the MODs, it was determined, highly influenced the Mole, and vice versa. Thus, they were investigated in parallel. For MODs, a chain-based and free-form architecture was introduced and compared to a lattice-based architecture. For a durable lattice-based system, a strong and precise connection between modules is crucial. This requires high precision of Moles. In Version 3, three different MOD geometries were tested: MoleCUBE, MoleCHAIN, and MoleSTRING. These helped define the path for future development and resulted in direction towards chain architecture. The use of permanently connected modules in a chain reduced the requirements for precision and sensing. because chains can be configured for space filling curves and intertwine themselves to solid structures. The essential ability to attach and detach from other modules was of secondary importance.

The active part, Mole, became almost fully soft with use of rubber-based materials such as TPU and ethylene propylene diene monomer (EPDM) rubber. For Version 3, inflatable parts were fabricated with 3D printing. The bellows in the soft body were adapted from industrially fabricated fork cover gaiters made of EPDM. By using of digitally controlled fabrication in combination with an industrial product (fork cover gaiters), a general problem of previous versions, leaking of air in inflatable parts, was minimized. For the first time, Version 3 fully tested peristaltic motion to overcome a distance of 1 m. Version 3 illustrated the potential of soft mechanisms, and its bending was already strong enough to move with the MODS. The problem was the slow speed of peristaltic motion: covering a distance of 1m took 5 minutes. To speed up movement, riding by gear wheels was tested as a replacement for peristaltic motion as well as to test the possibilities of the active part. Observations from testing revealed that the bending angle must be at least 180 degrees.

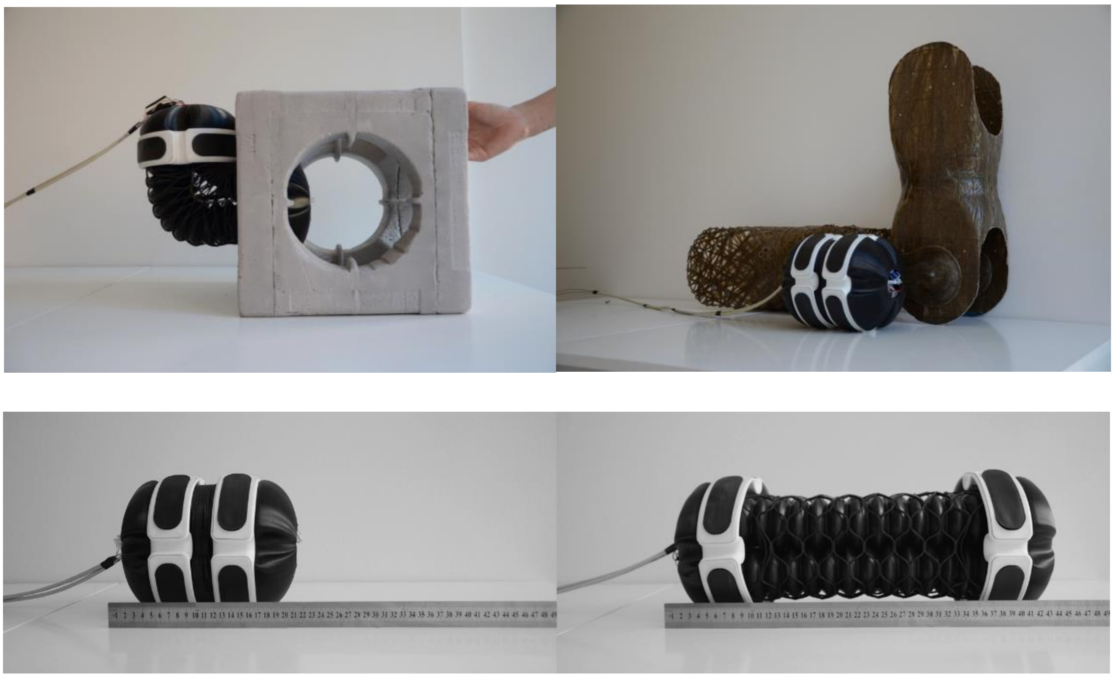


Fig. 45. Version 3: MoleCUBE (top left), MoleCHAIN (top right), Mole expansion (bottom left to right).

7.1.5 Version 4

Version 4 built upon results obtained from MOD selection with Version 3. The final decision towards chain architecture was achieved in this version (Fig. 46). Three aspects were found to be the most important for design of the Mole: weight, bending angle, and precision. First, the weight of all the passive and active parts should be reduced as much as possible. Second, the soft body must be able to turn a minimum of 180 degrees. Third, precision of all the components must be considered, even for the soft principles in which higher adaptivity is of concern. Passive and active parts were almost completely 3D printed for Version 4, including the rigid parts of the head and bellows for the soft body. To create faster and more precise movement, peristaltic movement was replaced by "riding" by means of a cogwheel powered by direct current (DC) motors. The cogwheel sped up movement of the robot, which covered a distance of 1m in 8 sec. Version 4 was able to move between modules as well as to assemble them. Even the prototype for Version 4 showed of the promise of the sharable actuator concept used in development of the next version.

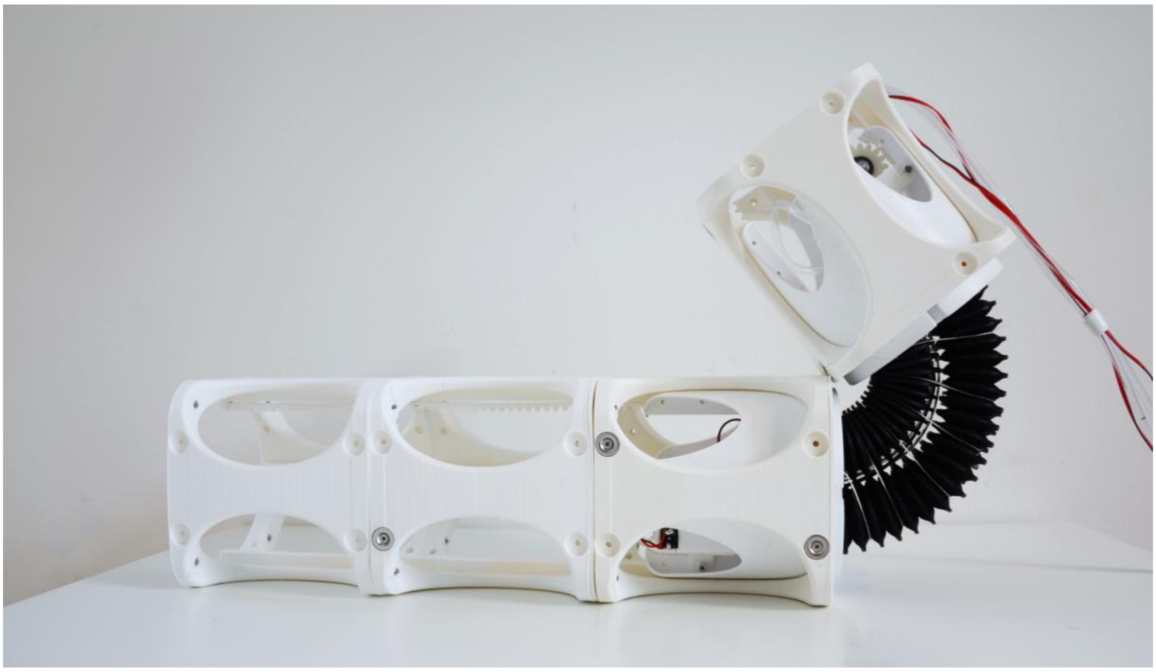


Fig. 46. Assembly process of MoleMOD Version 4.

7.1.6 Version 5

Version 5 extended the possibilities of Version 4. It used the same principles (3D printed soft body and riding motion). The novelty of Version 5 was the use of revolving casing for one of the heads used for revolving an adjustable hinge (Fig 47). Compared to previous versions, Version 5 focused more on the MODs. Two versions of MODs were developed. The first had an adjustable hinge connecting modules that could be rotated by revolving the casing into one of four directions. This MOD was fully 3D printed from PLA. A second version of MOD for this version was simplified and was significantly lighter as a result. This MOD was a “sandwich” made of EPS and carbon fibre reinforced polymer (CFRP). This made the module light and strong at the same time. The connecting “hinge” was placed only on one edge of the MOD. Thus, it could not be adjusted to more directions. This solution resulted in a reduction of the number of assembly combinations. On the other hand, it simplified the system which became more robust, lighter, and cheaper than 3D printed version.

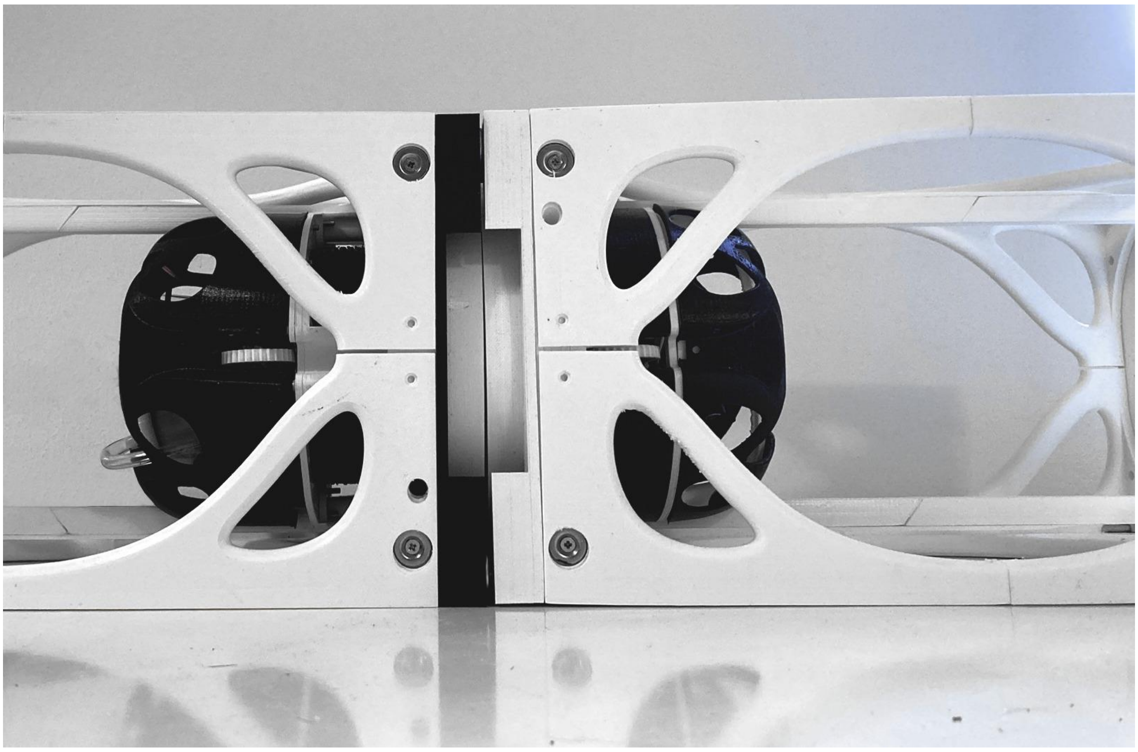


Fig. 47. Mole inside of 3D printed MOD in Version 5.

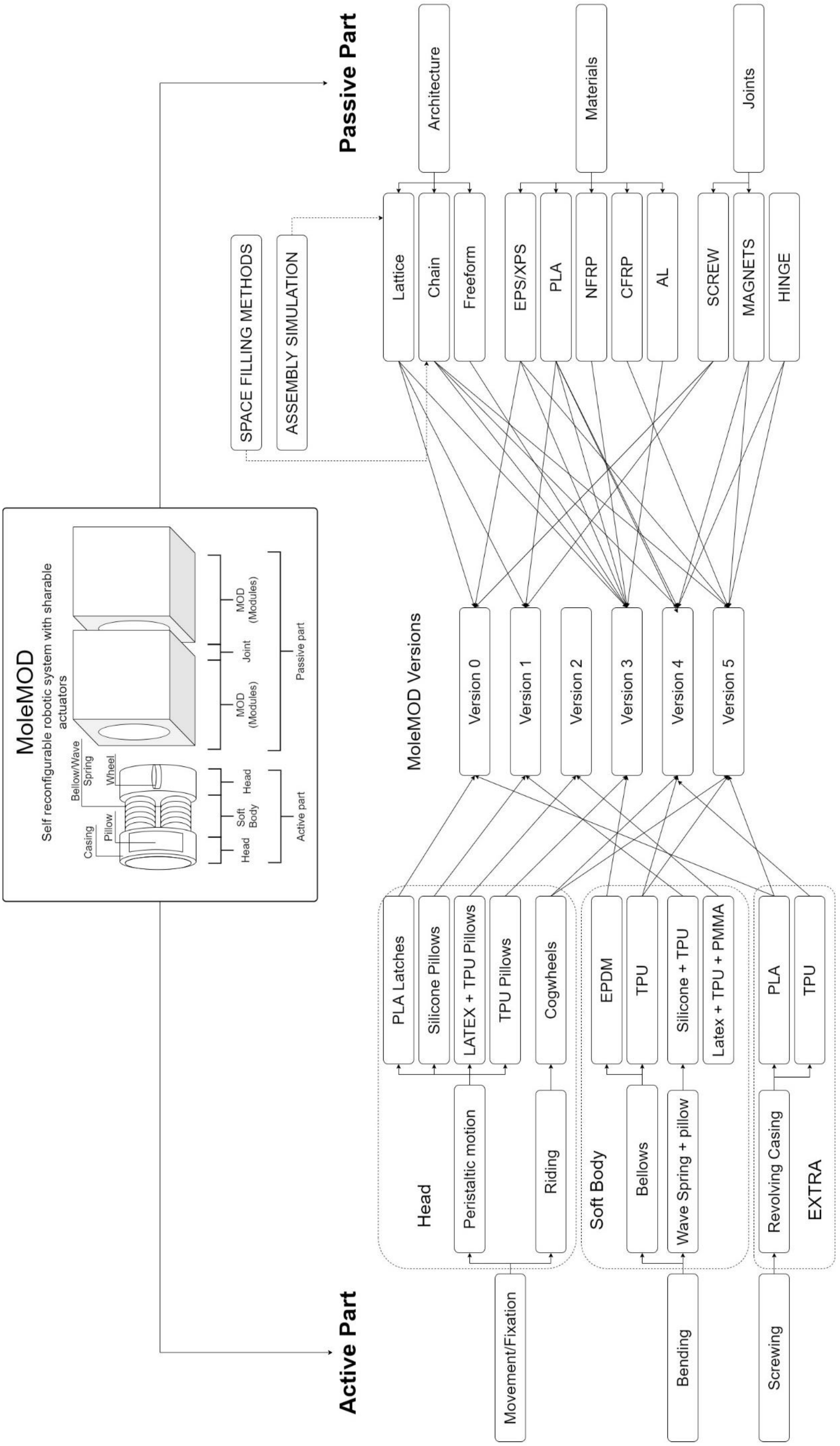


Fig. 48. MoleMOD Workflow.

7.2 MoleMOD Ingredients

7.2.1 Architecture

The functionality of the entire system for each version of MoleMOD was highly influenced by the selected architecture. The architecture defined the behaviour of each system as well as its physical components. The family of all MoleMOD versions used two main architectures: lattice and chain architectures accompanied by some testing of a free form architecture.

7.2.1.1 Lattice architecture

The original MoleMOD concept used regular lattice-based architecture (Section 4.1.1.1) consisting of cubic passive modules, MODs, with at least one tunnel in which Moles could operate (Fig.49). The lattice architecture was considered in Versions 0, 1, and 3a. A cubic shape of module was chosen because it is commonly used in modular robotics [112]. However, such systems are not restricted to cubic shapes; they can consist of arbitrary polytopes in order to build conglomerates without extensive limitations [119]. The goal structures can provide a variety of shapes by means of voxelization of a certain space and are not limited by fixed connections between modules. This reduces assembly complexity and maximizes dense packing [169] of a goal geometry by following the same regular matrix as a module. On the other hand, this architecture requires more attention to connections. Connections posed the most difficulties during the creation of different MoleMOD versions. Since MoleMOD uses a sharing actuator, connections are complex, and they require high precision in creating them. This, in combination with soft actuators, is a challenging task.

A lattice system does not always need to be homogenous but can be designed as semi heterogeneous when it is a reduced set of different modules following a regular grid [278].

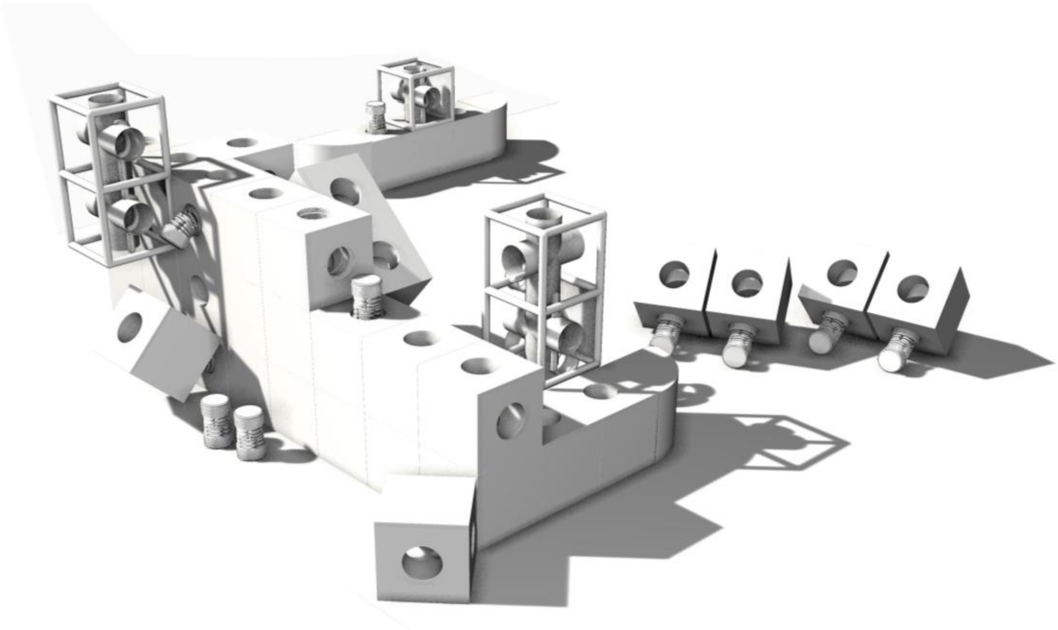


Fig. 49. Assembly with lattice architecture. Completely separable modules also facilitate mobile transportation by Moles.

7.2.1.2 Chain architecture

The high complexity of the joints in lattice versions of MoleMOD triggered interest in chain geometries, used in MoleMOD since Version 3 was introduced in 2019 [119]. In order for a lattice-based system to be durable, precise connection between modules is crucial. To simplify the entire system, a chain-based architecture was introduced (Fig. 50). Chain architecture requires more complex computation than lattice architecture and is not as versatile. However, the problematic connections are replaced by permanent joints, which helps with robot assembly and placing a reconfigured module into the right positions. This significantly reduces requirements and such robots can operate with lower accuracy because they are guided by a structure. The tested chain options in Versions 3b and 4-5 had cubic modules following a regular grid. Versions 4 and 5a tested connections with hinges moving in four directions to maximize versatility of the chain architecture. In the Version 5b, the hinge connection that moved in one direction could, in chain assembly, provide a relatively high number of possible reconfigurations.

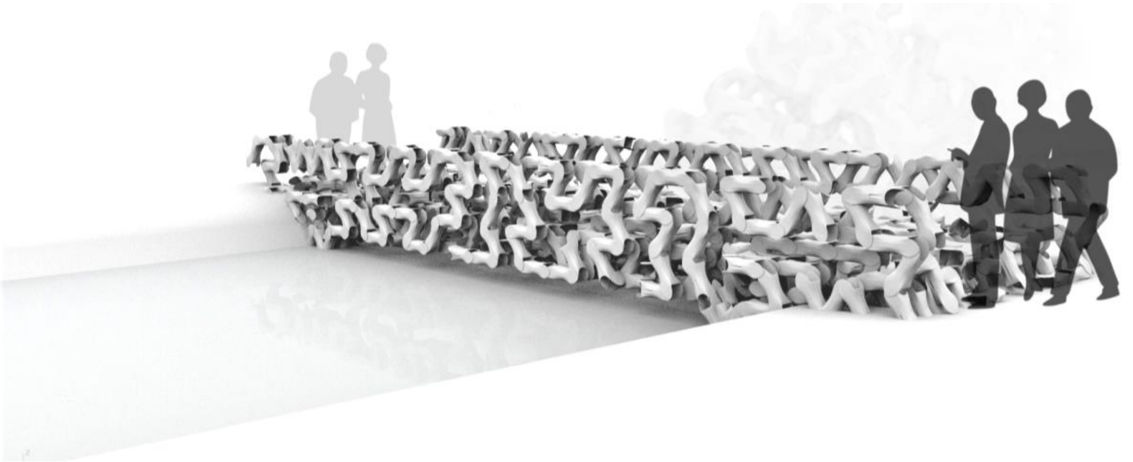


Fig. 50. Design of bridge self-assembled with chain architecture (MoleCHAIN).

7.2.1.3 Freeform architecture

A free form structure was used in Version 3c, “MoleString”. The idea was to avoid using discretized components. These were replaced by a continuous tube to allow bending in any direction by the robot from inside. The entire structure consisted of multiple Degrees of Freedom (DoF) adaptable to different morphologies. Development was negatively influenced by the material used to create String and it could not be fully tested, but the concept holds high potential. An aluminium tube was chosen because of its easy shaping profile and low weight. The string concept has its main advantage in DoF, which are almost infinite. This allows for the creation of a variety of shapes not defined by any regular lattice as well as better adaptivity to different environments (similar to soft robots). However, it is more difficult to control the position of a tube exactly and this leads to higher requirements for the robot, its navigation, and the precision of bending.

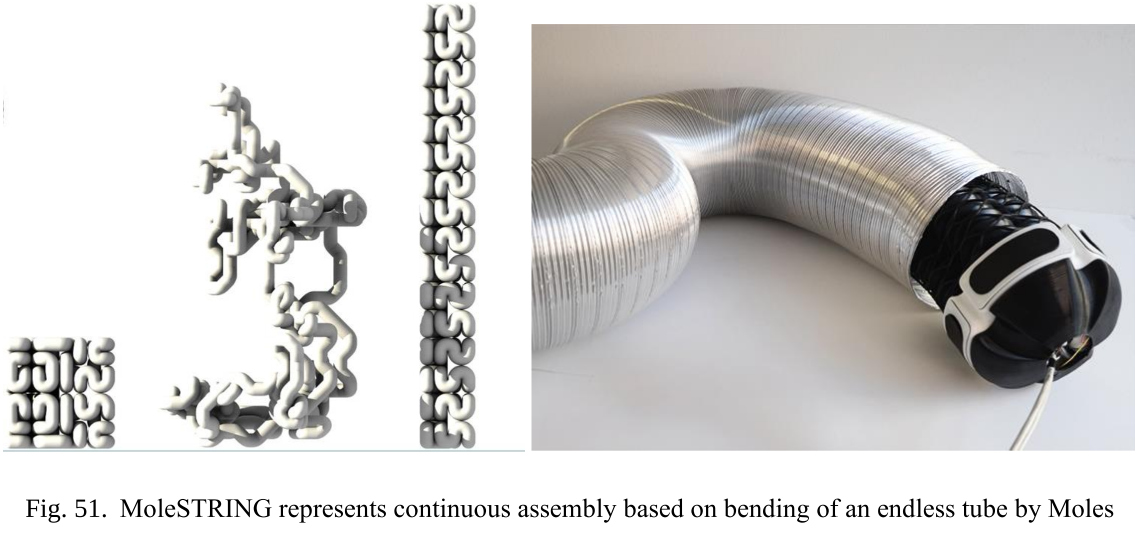


Fig. 51. MoleSTRING represents continuous assembly based on bending of an endless tube by Moles from the inside.

7.2.2 Passive Parts (MODs)

The passive parts are the building materials of any final product/building, and the materials used as well as structural design also influence behaviours after assembly. This section describes different experiments with materials, joints, and shapes for MODs.

7.2.2.1 Materials

One of the several advantages of the separable active and passive parts of the MoleMOD system is material independence. This is especially important for the passive parts (MODs). Theoretically, the passive parts can be made of almost any material, but in the author's experience, lighter materials allow for more precise fabrication. The goal of this dissertation is not to provide material solutions for the building blocks of such systems, but rather to make several recommendations based on observations from the MoleMOD project to date:

- The ability of materials selected should allow for high precision during fabrication. Actuators use soft robotics principles which are more adaptive than hard mechanisms.
- Different imperfections can arise, depending on the materials employed, and imperfect fabrication can block smooth movements of robots inside passive parts.
- For the fabrication of passive parts in Version 3 and 5, different lightweight materials were used and this led to lower power requirements for actuators and influenced the overall design of the system (actuators with higher power requirements would usually take up more active part space).
- The Version 5b introduced a sandwich made of fibre composite and EPS foam weighing only 200 grams but able to carry approximately 400 times its weight.

7.2.2.1.1 Fibre reinforced polymers

An increase in interest in sustainable architectural solutions in recent years has led to the introduction of fibre composites as partial replacements for traditional heavy materials (e.g., concrete, steel, and even wood). Fibre composites enable high strength-to-weight ratios, durability, and stiffness. This results in lightweight materials with excellent structural properties [279]. Fibre composites have two or more base materials that serve as a reinforcement and a matrix [279]. Fibres (carbon, glass, aramid, natural, others) are used for reinforcement, and they provide high mechanical strength in the direction of fibres. Different polymers (e.g., epoxy resin, thermoplastic resins, bio resins) make up a matrix that transfers loads between fibres. Combined correctly, composites achieve better material performance then their individual components [280].

7.2.2.1.1.1 Natural fibre reinforced polymers (NFRP)

Natural fibre reinforced polymers were tested in Version 3b. Two techniques were used: winding around a PLA skeleton(Fig. 52) and winding around a mould (Fig. 53).

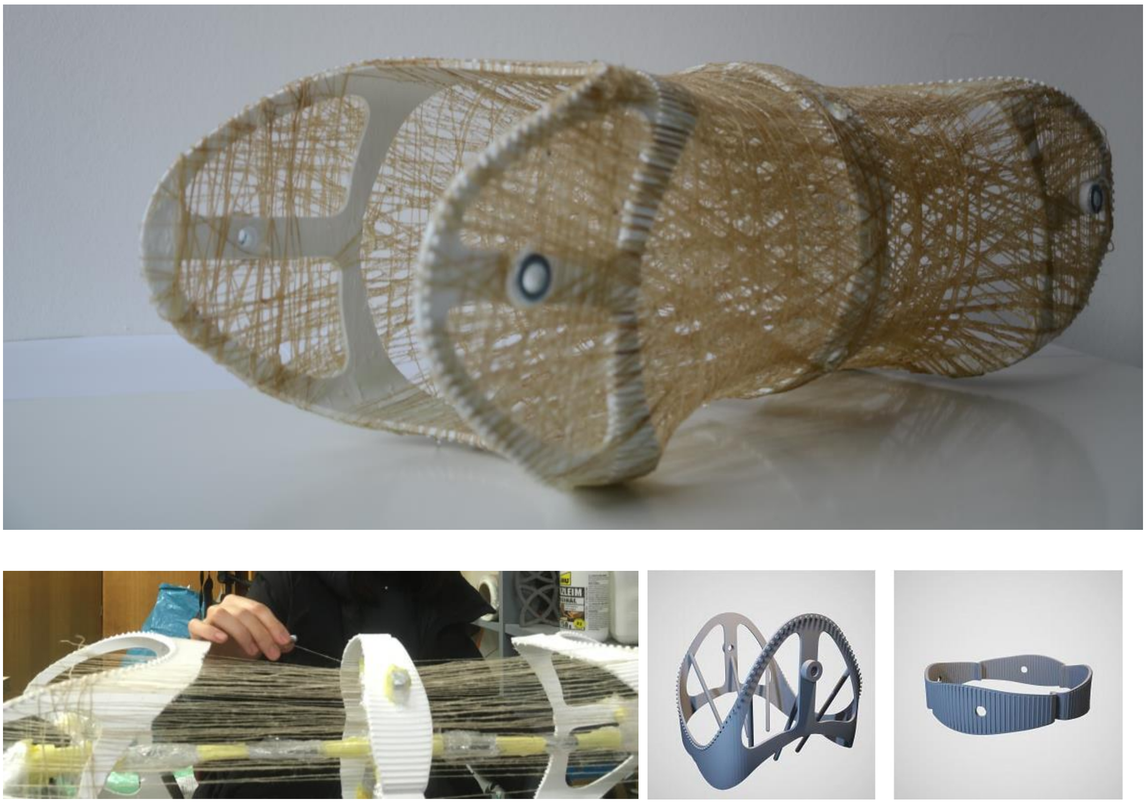


Fig. 52. MoleCHAIN passive part created by winding hemp natural fibre around a 3D printed PLA skeleton. Final passive element (NFRP), top. Process of manual winding (bottom left). Models for 3D printing (bottom right two images).

Fibres were also stretched around a PLA 3D printed skeleton which stayed in the final structure. Three 3D printed elements defined the correct radius and length of the element and later were connected using cured resin applied to fibres (three parts used EPIKOTE Resin MGS RIMR 135 and one part used EPIKURE Curing Agent RIMH 137). The element tested weighed only 750 g.

The quality of moulded elements depends mostly on the quality of the mould. With the element tested for MoleMOD, the fibres and matrix were manually wound around the mould. The specific shape of the chain element did not allow making the mould in one piece and this resulted in an inner mould than was more complex and less precise than if one-piece fabrication would had been possible.

Fig. 53. MoleCHAIN passive part created by winding flax natural fibre around a mould.

Natural fibres are a more sustainable alternative to petrochemical fibres and have several advantages over the latter: renewability, biodegradability, energy absorption, and lower cost. The processes described above are suitable for passive components, especially when a process will be automated [240]. However, lower mechanical properties and durability together with higher moisture absorption and varying quality when compared to petrochemical fibres must be taken into consideration [281].

7.2.2.1.1.2 Carbon fibre reinforced polymers (CFRP)

To increase the structural performance of the passive parts, the sandwich component combined a carbon fibre reinforced polymer (CFRP) with a foam core. For the core, a standard EPS board was cut into a specific shape and wound with 12 K unidirectional carbon fibre fabric infused with epoxy resin (three parts EPIKOTE Resin MGS RIMR 135 and one part EPIKURE Curing Agent RIMH 137). The resulting component was shaped by a cored material (EPS foam) and reinforced with CFRP (Fig. 54). With this combination, high structural performance was achieved because of the geometrical thickness of the component. A carbon cover was also used to protect the core material. For fabrication of passive elements, this approach was found to be highly effective. While such composite materials are not recyclable, this sustainability hurdle is partly overcome because in the overall concept, modules are reusable. For more sustainable solutions, natural fibres bound in bio-resin are recommended and this could be supported by using core materials such as foamed PLA [282] or metal foams[283]. To improve sustainability, subtractive processes should be avoided. Here, during fabrication subtractive processes were used for cutting foam-based EPS and XPS materials and, in the future, this should be replaced with expanding foams to fill the shapes of modules as a more sustainable process.

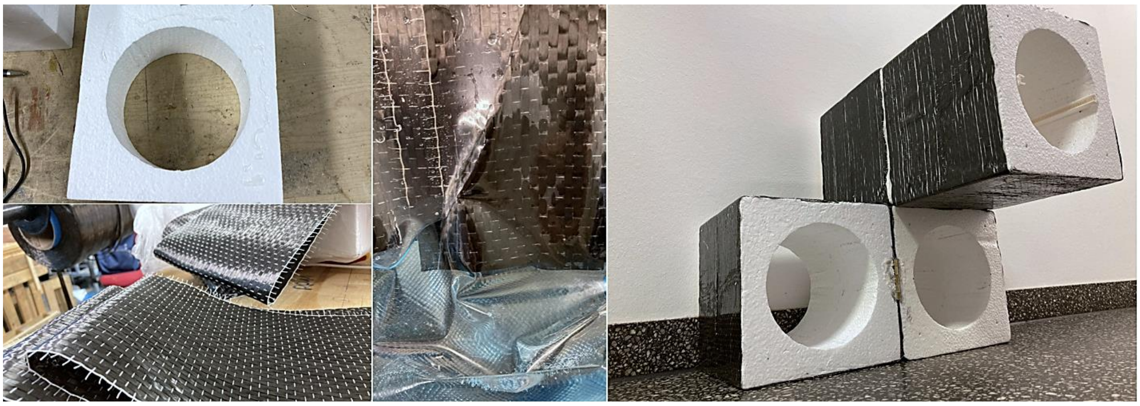

a b c

Fig. 54. Fabrication of passive modules (EPS core + CFRP reinforcement) for Version 5.b: (a) EPS core and 12 K unidirectional carbon fibre fabric (CFRP), (b) Vacuum infusion of CFRP by epoxy resin, (c) Final cured passive modules

7.2.2.1.1.3 Foams

The core material used can significantly reduce the weight of an overall module and can, in a sandwich composite, function as a thermo or acoustic insulator. There are few alternatives to oil-based foams like EPS or PUR (polyurethane).

7.2.2.1.1.4 Polyactide foam

Polyactide (PLA) is an aliphatic polyester derived from renewable feedstock. It has properties similar to EPS and could be used to replace oil-based foams. PLA foams are biodegradable and can be moulded as well as extruded. Bio-foams are gaining interest in the packing industry [282].

7.2.2.1.1.5 Metal foams

In recent years, metal foams are increasingly used where high strength energy, absorption, and lightweights are required. Such foams are fabricated in open or closed cells structures with foaming processes inside of moulds. Metallic foams have higher thermal and electric conductivities than polyactide foams [283].

7.2.2.2 Additive manufacturing and form-finding

For prototyping most of the passive parts (Versions 1, 2, 4, and 5), 3D printing with Ultimaker 2 and 3 FDM 3D printers was performed. The advantage of using 3D printers is clean fabrication without waste. While this precision is relatively high, industrial moulding techniques or precise milling to standardize properties and have higher accuracy should be used for final manufacturing. However, additive manufacturing would allow more complex shapes to be produced, which could reduce the amount of materials needed. Version 5a used an additive manufacturing approach and topology optimisation [284] was applied for a simple quadratic shape. The result was compared and combined to create a final symmetric shape (Fig. 55).

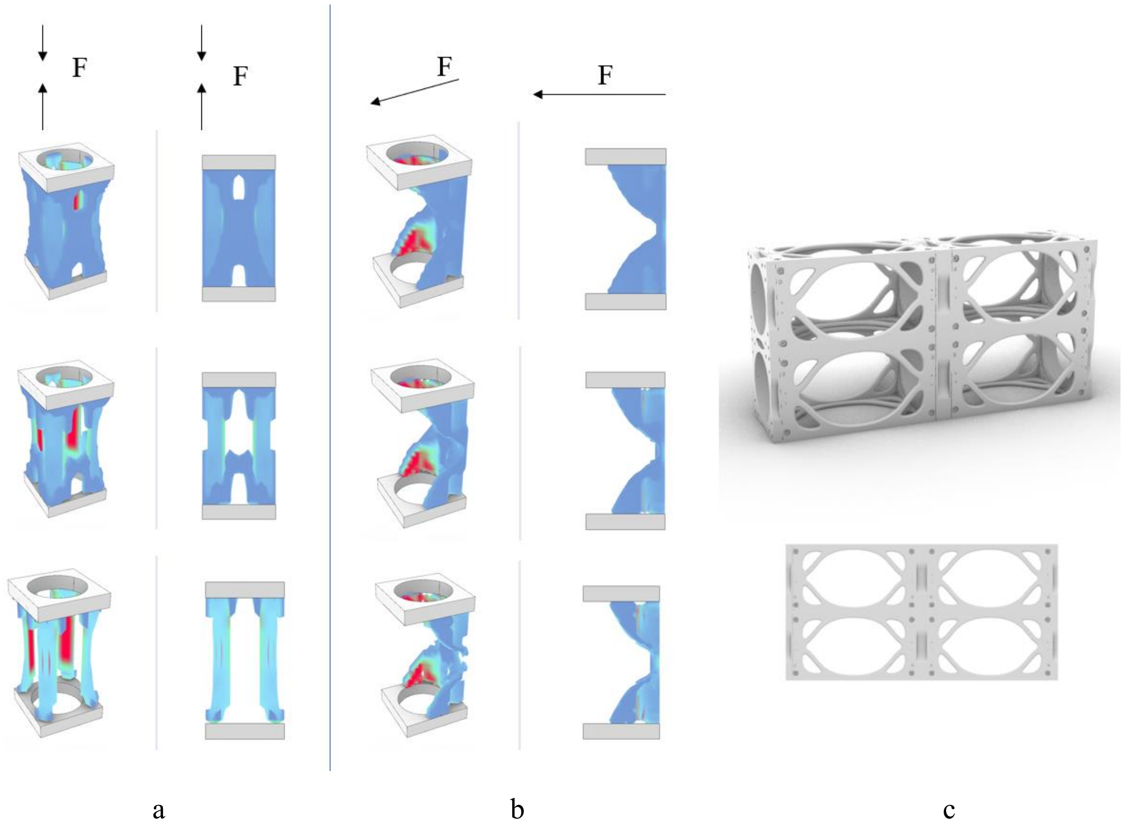


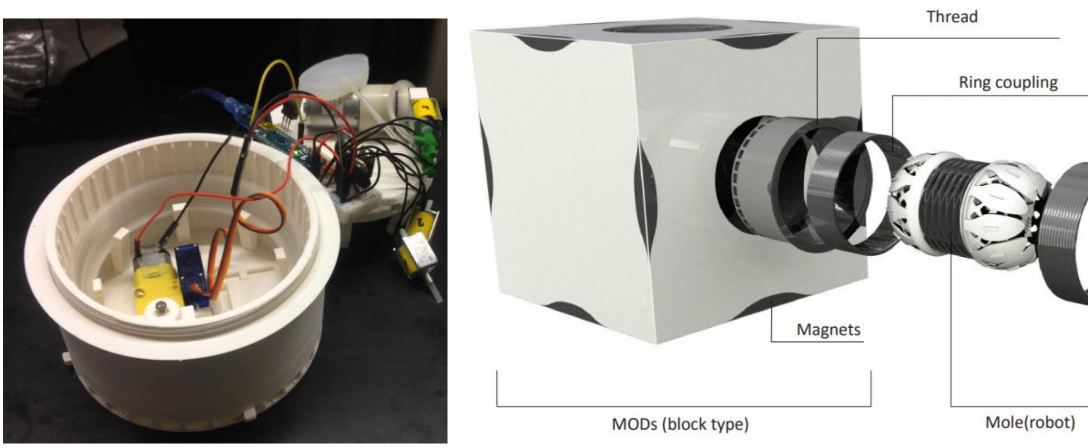
Fig. 55. Topological optimization of MOD (a.) Z-direction, (b.) X-direction, (c.) 3D model.

7.2.3 Joints

Joints are the connecting system between MODs and, in most state-of-the-art modular robots, joints employ mechanized connections like a “latch-catch” [112]. Such systems were avoided for MoleMOD because of their complexity (they require active parts, in most cases). For MoleMOD, the focus was on passive connections because the priority was to minimize MOD costs with simplicity.

7.2.3.1 Screw

Already in the Version 0, a special screwing system between MODs was developed. The novel system consisted of a thread and ring coupling. Each module had one thread at both ends of a chamber. By rotating a ring coupling in a thread, two modules are connected. Rotation was provided by the revolving head of the robot (Fig. 56). This kind of system holds high potential for larger scale applications because it is stronger than magnets or "latch-catches" typically used as screw joints. With MoleMOD, the goal was to design genderless screw joints to enable maximum configurability of assembled passive parts (not limited by connection gender). However, screw joints require extreme positioning and navigation precision to connect them, requiring strong and extremely precise robots. Screwed connections were mainly considered for lattice-based architectures in MoleMOD.



a b

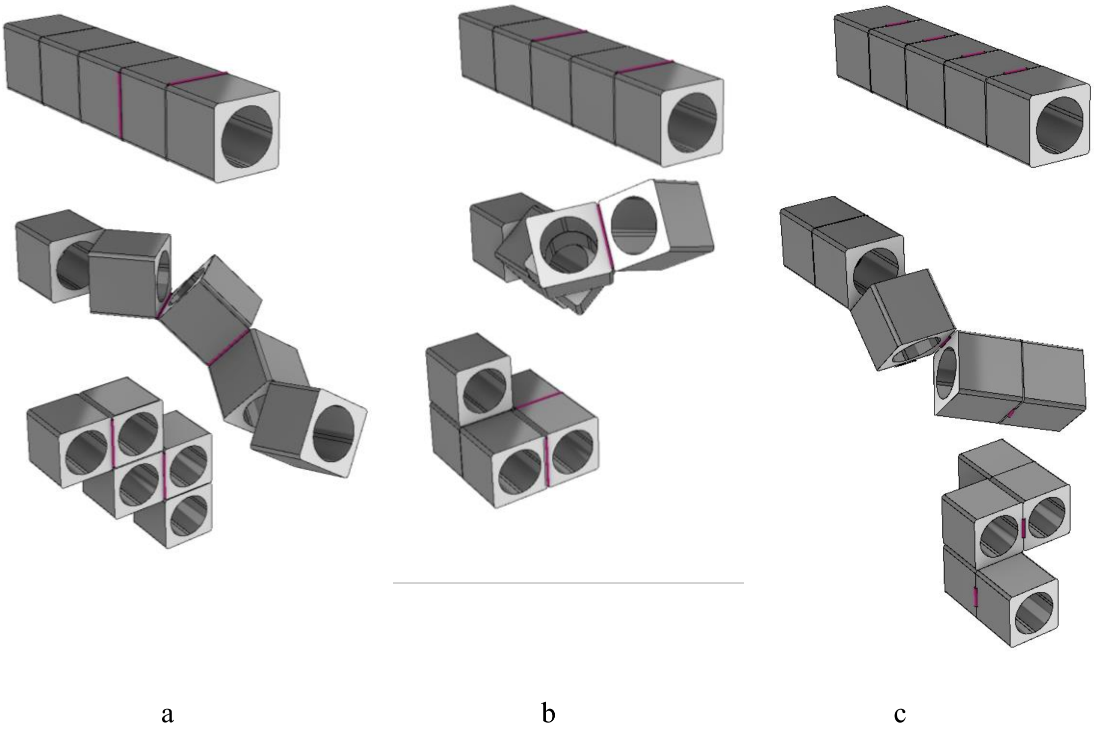
Fig. 56. Version 0 screw connection: (a.) Testing of screwing by revolving casing of Mole, (b.) 3D scheme.

7.2.3.2 Magnets

Magnets were used in most of the MoleMOD prototypes, and they are the simplest way to connect two modules. Such connections cannot, however, be considered for large-scale applications. They are also limited by polarity because only modules with opposite poles can be connected. Neodymium magnets were used for the MoleMOD prototypes.

7.2.3.3 Hinges

With chain architecture, modules become permanently connected. This significantly reduces the complexity of joints. Complex screw joint can be replaced with a simple hinge and magnets can be used to help with fixation. Such solutions are not suitable for industrial applications, however. Hinges also reduce the need for robot precision since the movement of the modules is guided by the axe of a hinge. Three methods of hinge strategy have been introduced and studied to date: hinge-hinge, hinge-rotation, and rotational hinge (Fig. 57). From MoleMOD Version 4, it is clear that hinges must bend over 180 degrees (not only 90 as in previous versions) in order to lock better in a final position.



a b c

Fig. 57. Three hinge strategies: (a.) Hinge-hinge, (b.) Hinge-rotation, and (c.) Rotational hinge.

7.2.3.3.1 Hinge-hinge

This type of hinge is placed on the one common edge between two modules. Each connector has only two options for how the performing module is configured: rotate around 180 degrees or stay in position. The direction of configuration is specified by which edge (1-4) is selected and the common face between modules. The selection of the edges can be predefined towards an assembled geometry shape. However, hinge-hinge has a limited number of configurations but only one hinge is used. Thus, overall system complexity is greatly reduced and this positively influences the durability of connections.

7.2.3.3.2 Hinge-rotation

This chain configuration is based on a sequence of connectors using rotation and a hinge. The edge position of a hinge does not need to be predefined in this kind of system and a whole module (with the hinge) is rotated against its neighbouring module. Thus, the hinge can rotate with the module in all four directions. The system requires a revolving head/casing in the active part. Rotation with the cubic module can be disadvantageous because with rotation of a module around its main axe, the module collides with neighbouring modules. For successful assembly, neighbouring modules around a rotational module must be eliminated.

7.2.3.3.3 Rotational hinge

This kind of hinge combines two afore mentioned kinds and is rotated by means of a ring placed between every pair of modules. This kind of system has no limitations in terms of configuration and every module can be configured in four directions. Modules with rotational hinges are more complex than those listed above and this increases the cost and weight of MODs (Fig.58).

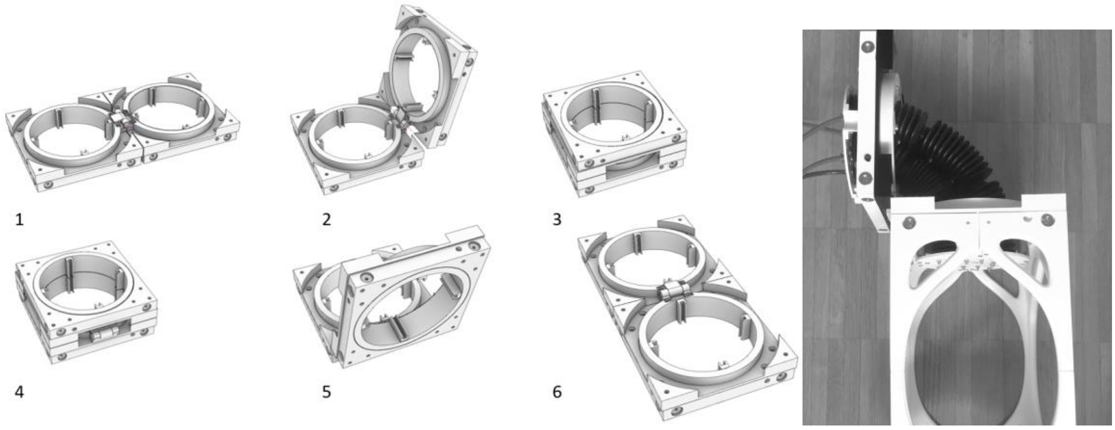


Fig. 58. Process of reconfiguration of a rotational hinge.

MoleMOD Version 5a used a rotational hinge and the advantage of this was higher stability of the overall system (Fig.59).

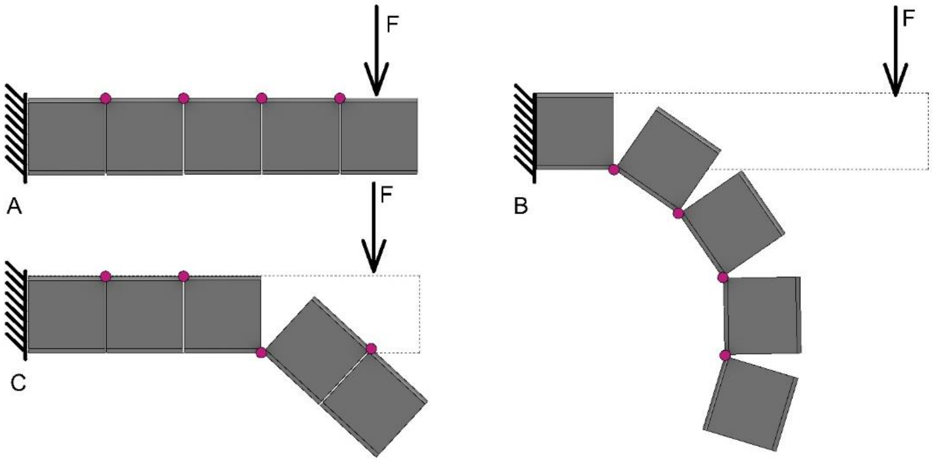


Fig. 59. Influence of position of a hinge the structural performance of a chain when force *F* is applied: (a.) Stability is maximized by rotation of hinges to upper edge, (b.) Stability is minimized by rotation of hinges to bottom edge, and (c.) Combination of hinge position towards a specific configuration.

7.2.4 Active part (Mole)

Since MoleMOD was first created, six types of active parts (Moles) have been developed. The principle from the beginning to the present has remained almost the same: the Mole consist of two heads which primarily provide movement and fixation. These heads are placed at both ends of a soft body that reconfigures MODs by bending of the body. The Mole is a unique system especially designed for this reconfigurable system with a sharable actuator. This section provides a technical description of Mole, demonstrated mainly with two prototypes, Version 3 and Version 5. Each has a different kind of movement and fixation.

7.2.4.1 Movement

From the beginning of the MoleMOD project, the aim was to create a robot mainly using principles of soft robotics [244] and which would be flexible and adaptive. Two approaches were investigated: peristaltic movement incorporating soft robotics principles [285] and riding movement using cogwheels and DC motors. In both cases, the soft body was compliant and consisted of inflatable bellows.

7.2.4.1.1 *Peristaltic movement*

Starting with Version 1, peristaltic movement was investigated for movement between modules. It was fully explored by the time Version 3 was developed. Peristaltic movement, so called "peristaltic crawling", is a type of movement used by earthworms utilizing contact with surrounding ground (channels) [264]. This kind of locomotion pattern changes between contraction and expansion of a body in an axial direction, influenced by the thickness of the body. By changing thickness in a radial direction, the body is fixed or released to the surrounding ground/channels [264]. In MoleMOD, this biomimetic inspiration was transformed into robot components in which the soft body provided expansion and contraction and inflatable pillows on the head expanded in a radial direction to keep the robot fixed in place while the soft body was moving (Fig. 60).

Peristaltic movement in a linear direction works based on a sequence which can be described as follows:

B_{on} – Back head fixed, B_{of} – Back head released, F_{on} – Front head fixed, F_{of} – Front head released, SB_e - Soft body expands, SB_c - Soft body contracts

(B_{on} F_{of} SB_e F_{on} B_{of} SB_c), (B_{on} F_{of} SB_e F_{on} B_{of} SB_c), (B_{on} F_{of} SB_e F_{on} B_{of} SB_c),…

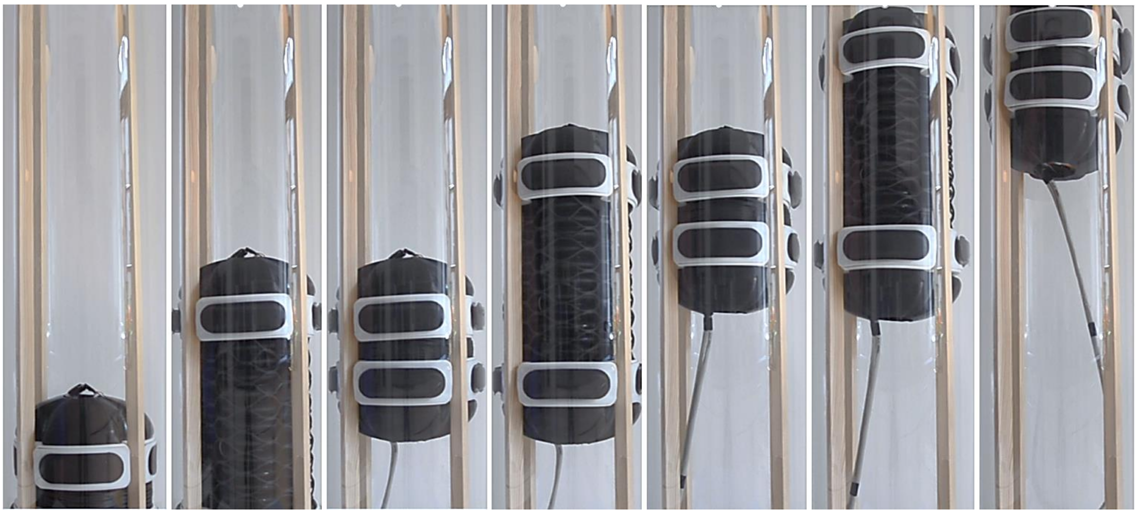


Fig. 60. Peristaltic movement in Z-direction of Mole Version 3. Testing the PMMA tube.

7.2.4.1.1.1 *Pillows*

In MoleMOD, pillows were essential part for fixation of head (B_{on} F_{of}, F_{on} B_{of}) during the expansion (SB_e) or contraction (SB_c) of the soft body when peristaltic motion was activated. Pillows were also used while the soft body manipulated with MODs. The pillows were fabricated from soft materials like silicon, latex, and TPU. Controlled compression and decompression of air inside the pillows was controlled by opening and closing a solenoid valve placed in the front of the pillow as well as by a switching air pump. From the first experiments, it was clear that the material for the pillow needed to be resistant against rupture resulting from contacting the surface of the MOD.

7.2.4.1.1.2 3D printed TPU pillows

In Version 3, pillows were completely 3D printed from a flexible TPU filament. The Ultimaker 3 FDM 3D printer was able to print two different materials in parallel. This was essential for the interior of the pillow, which needed to be filled during printing with a washable material (e.g., PVA, Hips) to avoid connecting the bottom and top surfaces of the interior space. For the pillows, an Ultimaker TPU 95a flexible filament was used to support the washable Ultimaker PVA filament. The final 3D printed pieces were only 1.6 mm high and consisted of 16 x 0.1 mm layers of TPU. The pillows expanded when air pressure was applied (up to 30 mm with a maximum pressure of 3 bars). Such high expansion was achieved by using foldable geometry. An advantage of 3D printing was direct integration of the air inlet, often critical in order to avoid leakage. 3D printed pillows have the potential to be made in specific shapes when moulds cannot be used to fabricate them. From the MoleMOD project experiences, the author recommends using them under rather small pressure to avoid delamination stemming from layering of the filament. The quality of the printing process is crucial, because even small imperfections during printing can lead to small holes in the pillows.

a b

Fig. 61. 3D printed pillows: (a.) Layers for 3D printing in Ultimaker Cura, (b.) 3D printed TPU pillows in use.

The peristaltic motion provided by pillows is advantageous because of strong fixation inside the MODs, which allows movement even in a vertical direction. The softness of this kind of mechanism is more protected against damage when compared to mechanical approaches. Problems include speed of movement and frequent stacking inside MODs. The latter is influenced by the length of the head, which should be longer than the diameter of the head. This requires more space for a head inside MODs.

7.2.4.1.2 Riding movement

When presenting MoleMOD, a commonly asked questions is why peristaltic motion was used instead of riding (i.e., using wheels for motion). Versions 4 and 5 introduced cogwheels for movement (Fig.62). The cogwheels were used because of their ability to be fixed in position as well as to move faster than the peristaltic versions. However, higher precision during fabrication is required and they can be more easily damaged than soft pillows. With cogwheels, movement can be discretized by a number of cogs and this results in better control. The cogwheels require cog tracks in MOD.

For this project, wheels were powered by a 12V DC motor controlled using an Arduino Motor Shield (L293D).

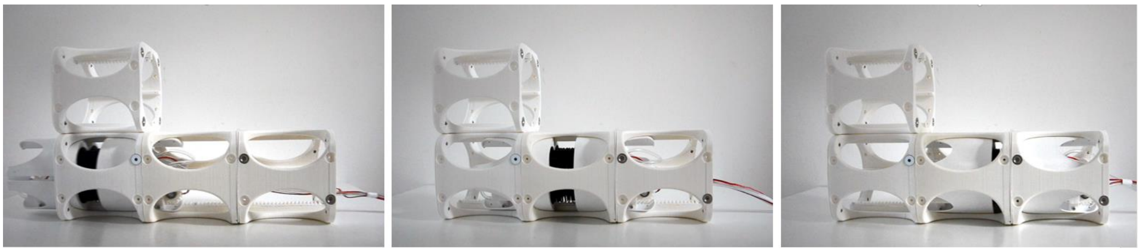


Fig. 62. Riding movement inside MODs in Version 4

7.2.4.2 Bending

Reconfiguration by bending was the best option for moving modules tested during the MoleMOD project to date. Another option considered was rotating modules against each other, which is generally easier in terms of connection and stiffness when used in modular reconfigurable systems but which is highly problematic because of movement of the sharable actuators (Moles). The soft body which provides bending was found as the most challenging part of the whole system. It had to achieve long expansion stiffness, and controllability in four directions (if cubic MODs are used).

7.2.4.2.1 Soft body

The soft body provides bending as well as movement when peristaltic movement is used (Version 1-3). Two soft body approaches are described below: wave spring +pillows and bellows.

7.2.4.2.1.1 Wave spring + Pillows

This method was used in MoleMOD Version 2. It consisted of a compliant wave spring composed of PMMA rings and small inflatable hybrid pillows. The spring shrunk in a longitudinal direction opposite to the direction of inflation provided by the pillows. This combination stabilized the soft body. Inflatable pillows were placed between the layers of spring. The small pillows were hybrids of latex balloon and TPU containing a net which protected the system from uncontrollable expansion of the latex balloon. The layers were completed by magnets that helped reach the original state of the spring (Fig.63).

The expansion of the body changed when compared to the original state and was only 1.5 times, not sufficient to reach the bending angle of 180 degrees. Another problem arose when force was applied in a radial direction to the body. This force cannot be higher than the resistance of the wave spring and pillows.

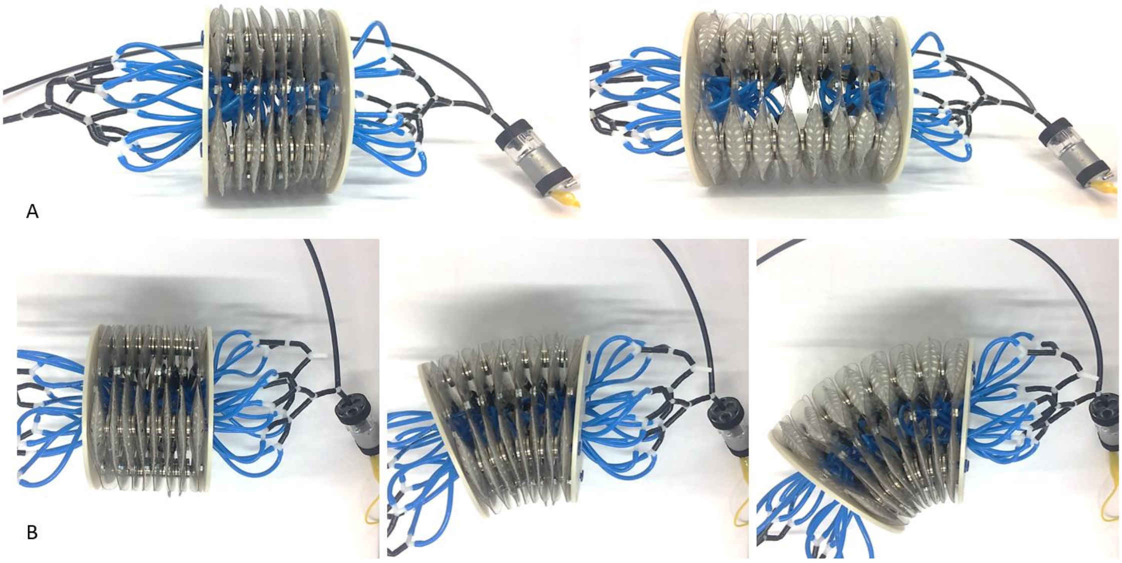


Fig. 63. Soft body of Version 2 and its reconfiguration: (a.) Expansion in longitudinal direction ca. 1.5 times, (b.) Bending angle ca. 45 degrees.

7.2.4.2.1.2 Bellows

To reach higher expansion and stiffness, a combination of vacuum and inflation was introduced in Versions 3 to 5. Bellows can be bent into four possible directions and stretched during peristaltic motion.

Fig. 64. Bending in different directions by synchronisation of the vacuum and compression in Version 3.

Four rubber bellows were placed between the heads. By controlling the change in pressure and the vacuum, the bellows were able to stretch, squeeze, and bend (Fig 64). By combining pressure and vacuum, the soft body was kept stable and was able to operate with the higher loads needed for transforming the passive MODs. The vacuum and pressure loads worked in the opposite direction and this made the soft body stable without the need for opposite forces provided by other devices or for materials such as wave springs. A vacuum can provide very strong stabilization and this can make a robot almost rigid in certain configurations. The bellows used were fabricated using EPDM rubber closed with an EPDM rubber cap with an input for air supply in MoleMOD Version 3.

7.2.4.2.1.3 3D printed bellows

In Version 4, the bellows were 3D printed first. 3D printing is time-consuming, but a geometry can be manufactured exactly according to the needs at hand. In Version 5, the bellows were discretized into three parts to provide replicability in case a bellow was damaged (i.e., the whole length of the bellows would not have to be fabricated again). In Version 5, 3D printing was improved and a PVA disposable material did not have to be used. This was achieved by optimized supporting pattern, which protected the connection of two layers when the bellow was printed and which enabled them to be easily detached after printing by means of low air pressure (Fig. 65).

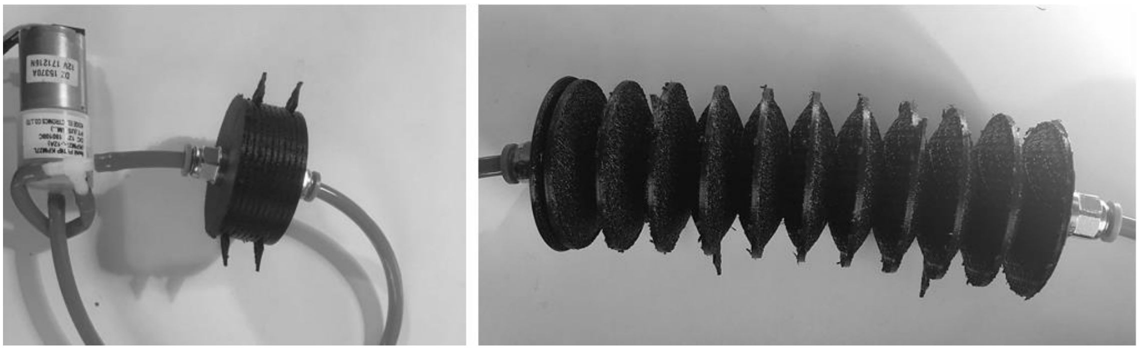


Fig. 65. Detaching process with low air pressure after 3D printing.

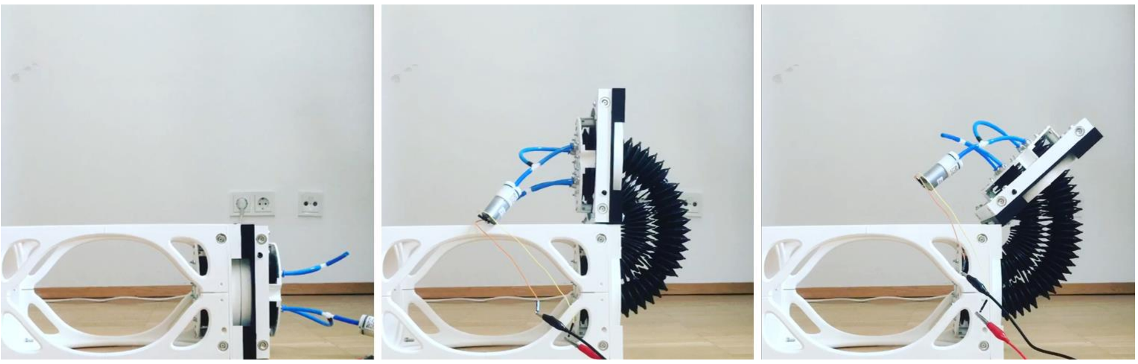


Fig. 66. Reaching bending angle of 180 degrees in Version 5 with modular 3D printed bellows.

The combination of vacuum and compression was found to be very effective for control and contributed to stiffness in the soft body, and the introduction of 3D printing allowed for the creation of custom-made parts, a necessity when bespoke robots are prototyped. 3D printed TPU bellows enabled higher expansion than industrial-made bellows. However, 3D printing errors can cause leaks in certain places.

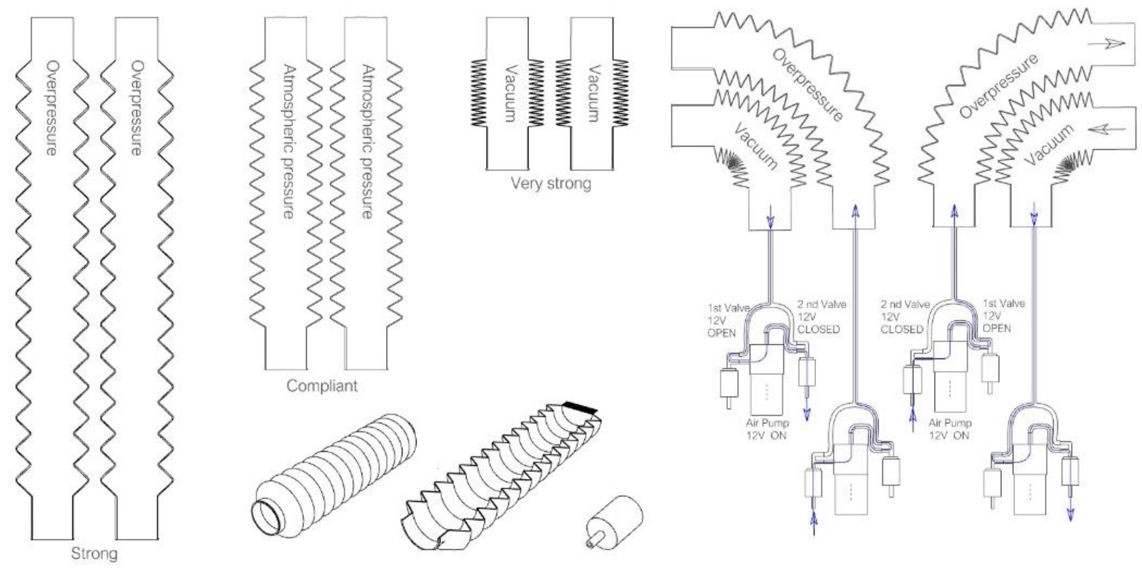


Fig. 67. Principle of air distribution in a soft body within bellows for air control (vacuum and compression),

7.2.4.3 Electronics

Electronics were used for controlling air pumps, servos, and solenoid valves. Arduino boards were used and programmed using Arduino IDE software. For digital control of mosfets, mosfet boards, relay boards, and motor shields pumps, solenoids and servos were used. Several sensors were tested including pressure sensors and distance sensors but sensing and robot control were not the main focus of this dissertation project.

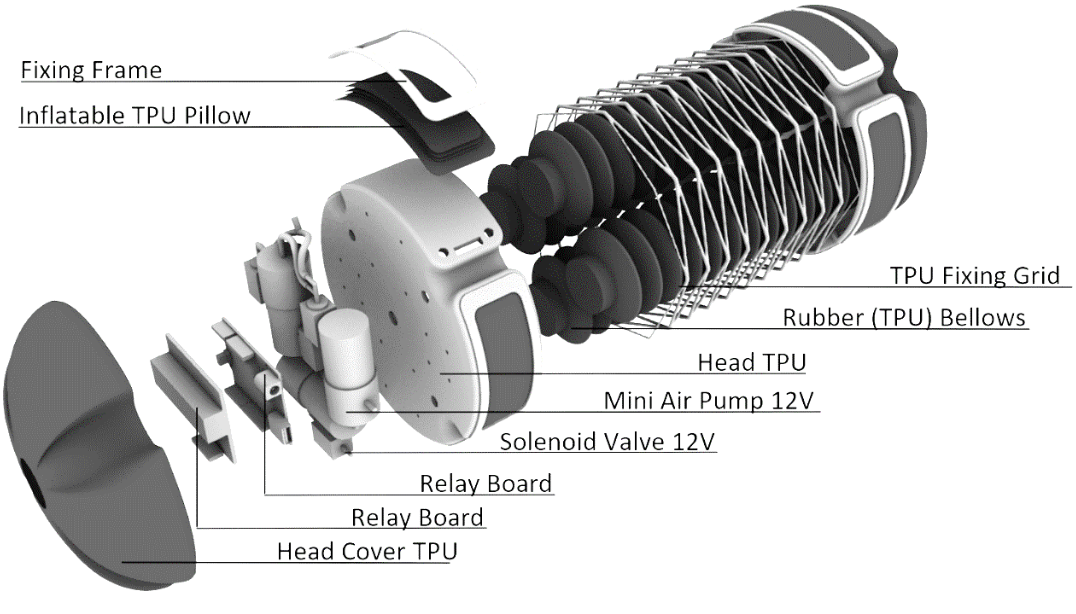


Fig. 68. Mole Version 3 components.

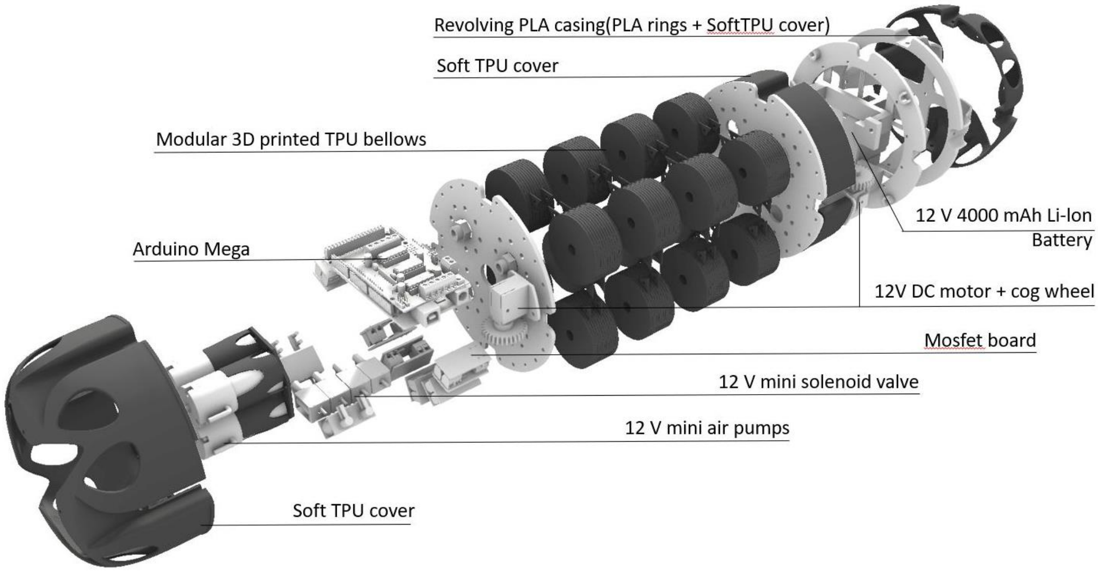


Fig. 69. Mole Version 5 components.

7.2.5 Simulations of lattice architecture

For the lattice based architectures, the planning algorithms were investigated by students from the CTU in Prague's Faculty of Electrical Engineering, Department of Control Engineering, under the supervision of Dr. Kulich and Dr. Přeučil [286], [287].

Two simulations were developed: 2D assembly and 3D assembly planning.

7.2.5.1 2D assembly planning

The simulation tested MoleMOD's simple movement in a heterogeneous environment using the Gazebo open source simulator [288]. Planning was based on an A* search algorithm [289] that searched the states represented by passive blocks. The space was assumed as two-dimensional, represented with a two-dimensional matrix. Two types of movement were tested: simple movement between modules, and lifting of blocks. To evaluate performance, cost efficiency was applied when planning the search for movements in order to use the cheapest path from the start position to the goal position. To simulate movement, MoleMOD Version 1 was simplified in order to utilise geometries with the lowest number of possible faces. For this reason, the tunnel in MOD and Mole had a square profile. The active part simulated MOD's lifting so that its soft body could turn around 180 degrees. It did not consider inflatable pillows for fixation; when fixation was needed, Mole simply stopped. The simulation model consisted of three main cubes, four prismatic joints, two universal joints, and four small immaterial cubes between joints (Fig 70). This simplification was necessary, as noted above, for ensuring efficient computation time and to avoid the simulation bugs that arise when using complex geometries.

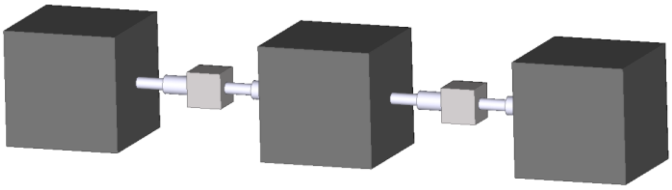


Fig. 70. Simplified model of Mole for the Gazebo simulator [286], [288].

The simulations successfully tested (Fig 71) basic planning for a model with cost effective movement. The computational time needed to find a solution with more robots was significantly slower [288].

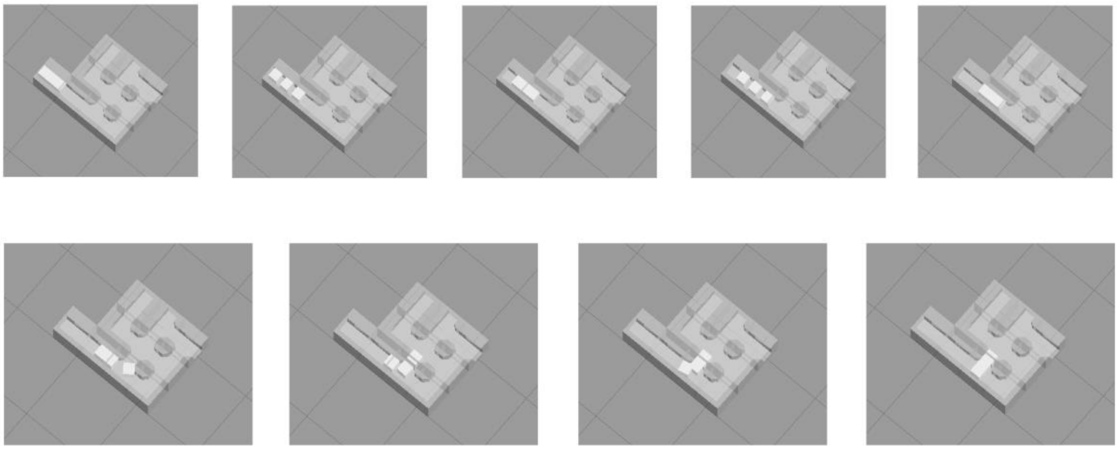


Fig. 71. Simulation of movement of Mole inside MODs in the Gazebo simulator [286], [288]. (Picture provided by Michaela Brejchová)

7.2.5.2 3D assembly

The goal of this planning algorithm was to simulate the assembly of MoleMOD in a three-dimensional space. This process was based on decomposition of the initial cubic conglomerate of boxes towards a final shape. The process was divided into three main steps: sorting, planning and optimization.

Sorting

Before sorting was performed, all actions for reconfiguration of one module were defined such as "rotation: up, down, left, and right". The goal of sorting was to find the correct placement order for these blocks.

Planning

Sequence planning was used for robots and blocks in order to define how to move a block from position A to position B.

Optimization

The goal of optimization was to reduce building time.

Student described a 3D planning method that was able to simulate construction of a simple bridge and pyramid. The bridge consisted of 234 blocks and was created with 4 robots. For manipulating a starting "cube conglomerate" into a final bridge, modules were reconfigured in 2,653 steps and the robots performed 7,941 steps [287] (Fig. 72).

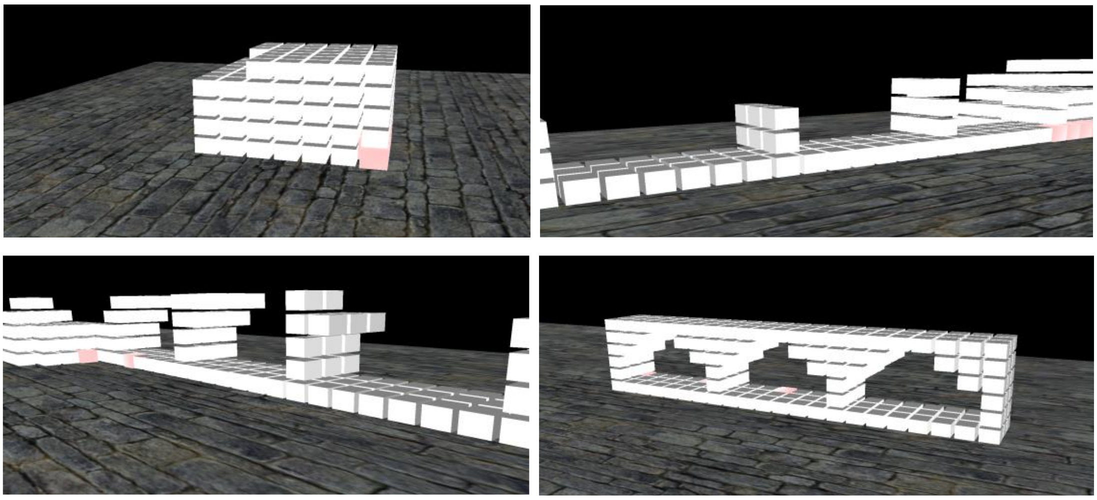


Fig. 72. 3D planning method for assembly of a simple bridge [287]. (Picture provided by Michal Urválek)

7.2.6 Space filling for chain architecture by evolutionary optimization

The MoleMod system is based on a voxelated space configuration, which consists of boxes with different sizes in a regular 3D or 2D lattice. The interaction between the Modules (MODs) follows a 1D chain architecture, even though it fills a 3D space. The 1D logic makes the computation more complex in comparison to simple voxelization of space. In chain-based architecture, continuity and interconnection also has to be considered. Parameters which define the assembly logic also define turning points and continuous robot movement inside of a structure.

Different two strategies for the 1D chain filling space were investigated via simulations using evolutionary optimization performed with Silvereye and Octopus plugins for Grasshopper and Rhinoceros.

7.2.6.1 Input parameters

- *Size of modules:* This parameter is significant for the number of discrete modules. The size of a rectangle or box influences their number inside the object which will be filled.
- *Number of modules:* This parameter is usually defined by the size of the module. This influences the entire precision of the system and computational time as well.
- *Stacking:* Modules are in described simulations (2D) simplified to their central point. Their configuration is provided by the rotation of a neighbouring module around a turning point (2D) space or edge (3D) space(Fig. 73).

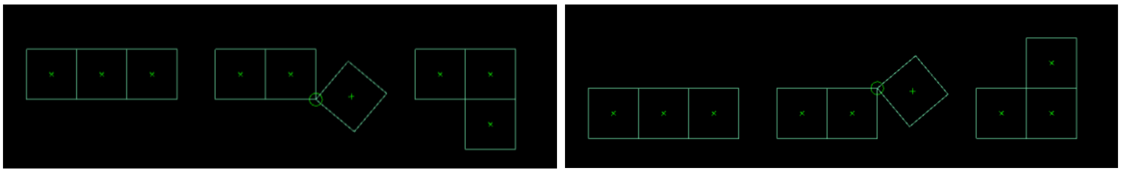


Fig. 73. Stacking (reconfiguration) of cubes by rotation around one turning point (edge).

- *Turning points:* The number of turning points should be as low as possible in order to save energy, necessary for reconfiguration of the robots. The robot (Mole) has the most difficulty navigating turning points. In future similar implementations of this concept, turning points should be minimized.
- *Self-intersection:* The assembly logic is designed to avoid any self-intersections or position duplications.

7.2.6.2 Computational tool

Space filling is provided by evolutionary optimization. The position of points is optimized through multiple iterations towards a goal state that avoids self-intersection and minimized turning points.

Turtle Path

The initial curve defining the path, points, and position of the modules follows discrete chain logic using a turtle graphic simulation [290]. Turtle graphics works as follows: each function has different code which the turtle reads in a linear process, step-by-step, drawing lines behind it.

Some functions used by Grasshopper Rabbit plugin include:

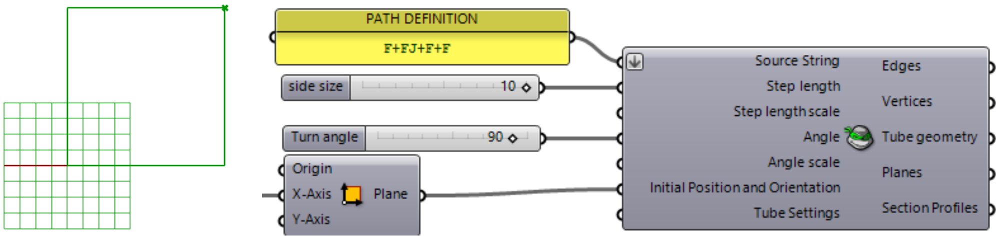
“F”: Move one step forward in a predefined distance and draw line.

“f!: Move one step forward in a predefined distance without drawing a line.

“+”: Turn left.

“-“: Turn right.

“J”: Drop point.



PATH DEFINITION

F+FJ+F+F

side size 10

Turn angle 90

Fig. 74. The Turtle definition (F+FJ+F+F) for the simple square with a point in the top right corner.

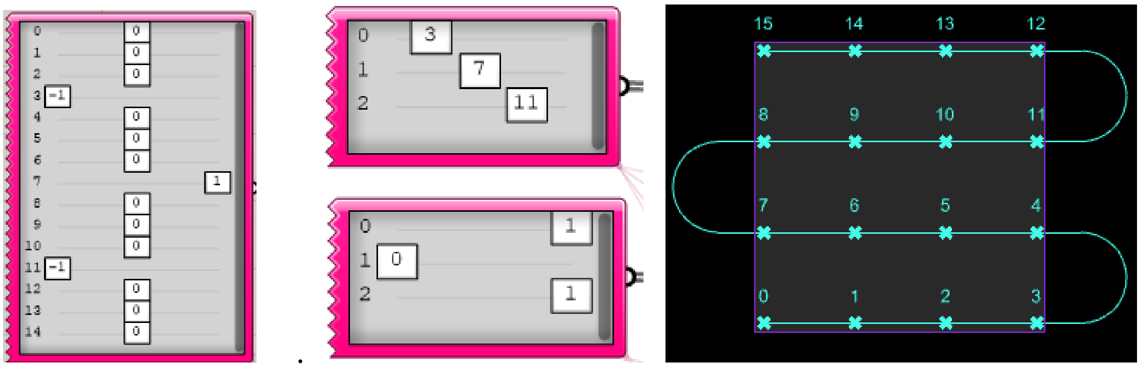
Two Turtle-based approaches were tested to define the specific space filling for MoleMOD, named: chain member subdivision and chain row subdivision.

7.2.6.3 Chain member subdivision (CMS)

This logic is discretized into single members. Each member in one iteration has one of three tasks: Turn right 180°+Drop point, Turn left 180°+Drop point, or Forward+Drop point). Tasks, during evolutionary optimization, are represented by numbers (-1, 0, 1). The algorithm searches for the combination of numbers where the sum of goals borders zero.

Codes for individual tasks:

Task	*Turtle code*	*Representing Number*
Move forward + Drop point	*FJ*	0
Turn left 180° +Drop point	*F+F+FJ*	-1
Turn right 180° +Drop point	*F-F-FJ*	1



a b. c.

Fig. 75. (a.) Chain member subdivision (CMS), (b.) Chain Row Subdivision (CRS), (c.) Space-filled geometry, geometry examined (purple square).

7.2.6.4 Chain row subdivision (CRS)

This logic is discretized into rows considered in one iteration. The algorithm searches in two levels for the position of the turning point and its direction (*Turn right 180°+Drop point, Turn left 180° +Drop point*) while the rest of the members stay at a *Forward + Drop point*. Turning tasks, during evolutionary optimization, are represented by numbers (0, 1); position is represented by integer numbers of domain (0 to list size). The algorithm searches for the combination of position numbers and turning direction where the sum of goals borders zero.

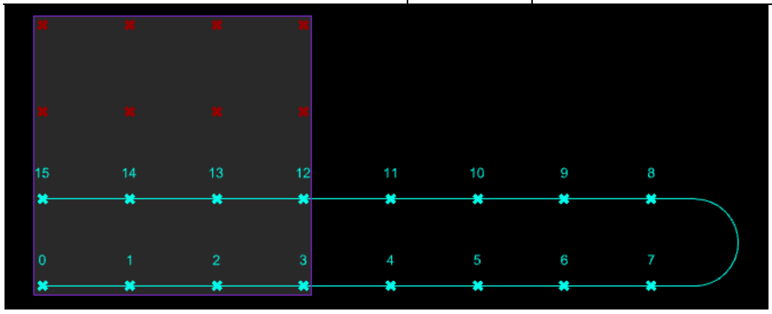
Task	*Turtle code*	*Representing Number*
Move forward + Drop point	*FJ*	-
Turn left 180° +Drop point	*F+F+FJ*	0
Turn right 180° +Drop point	*F-F-FJ*	1

Silvereye Solver

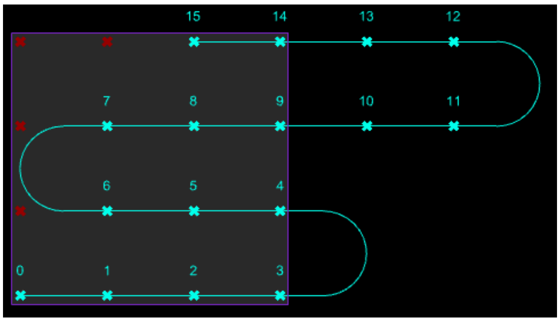
	Test nr.	*CMS*	*CRS*
Number of iterations (Fitness)	1	X(25)	6(0)
	2	*X(29)*	6(0)
	3	*X(52)*	12(0)
	4	*X(65)*	21(0)
	5	*X(25)*	9(0)
Average	*1-5*	*Not Solved*	9

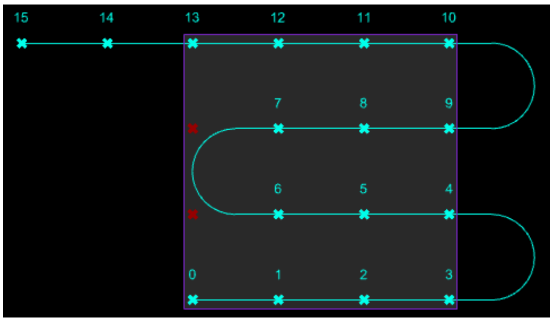
CRS Method Evolutionary Optimization solvers

	Test nr.	*Silvereye*	*Octopus*
Number of iterations (Fitness)	1	6(0)	X(0)
	2	6(0)	24(0)
	3	12(0)	X(0)
	4	*21(0)*	11(0)
	5	*9(0)*	11(0)
Average	*1-5*	*9*	15.3 (without Non- solved tasks)



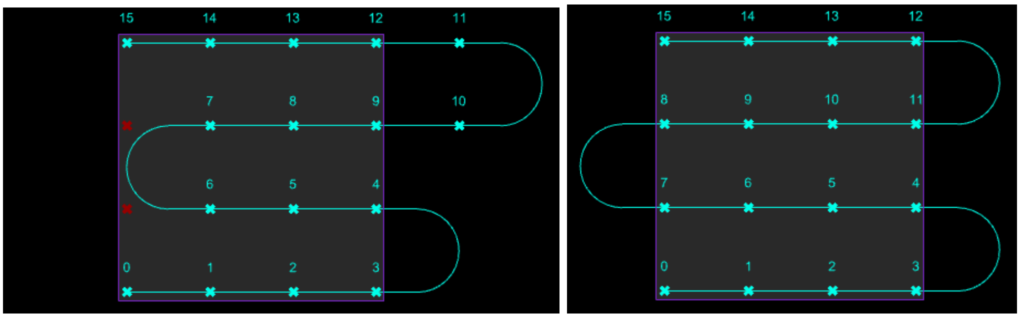
Iteration 0, Fitness Value = 224





Iteration 1, Fitness Value = 72

Iteration 2, Fitness Value = 36



Iteration 3-4, Fitness Value = 26

Iteration 5, Fitness Value = 0

Fig. 76. Iterations of Chain row subdivision Evolutionary Optimization.

7.2.6.5 Results

Chain row subdivision operated with a combination of a smaller number of tasks within one interaction, and this positively influenced the speed of the searching algorithm and reduced computational time. Chain row subdivision depends on the prediction of the number of turning points and can be estimated from the number of rows, in the case of a 2D geometry. In Figure 76, both systems are compared and the examined geometry consists of a preliminary linear assembly of modules. In this case, CRS was faster because it operated with a lower number of variables divided into two levels (position of turning point, turning direction). For cases in which the preliminary assembly of modules is non-linear, CMS should be selected.

Both methods were tested on a 2D simple square geometry with a preliminary linear assembly consisting of 16 modules stacked into 4 rows. The starting point and vector of movement which defined the position of the next module was predefined to the correct direction. Evolutionary optimization was calculated via the Grasshopper plugin, Silvereye, and every tested iteration started from the same original assembly. The swarm size setup in Silvereye was 40 and the number of iterations was limited to 100.

Both CMS and CRM methods had difficulties solving tasks with a higher number of modules. Even though the CRS method was faster, with it, the number of the iterations was quite unpredictable and measured samples ranged between 6 to 21 iterations. Both solvers could cause Rhino 3D to crash. In future investigations, other methods and solvers should be considered for the space-filling method. The tests confirmed the computational complexity within chain architecture.

7.3 Summary

Six versions of MoleMOD were developed and two main approaches were introduced. The first investigated peristaltic motion and the second, movement by means of cogwheels. Most effort was devoted to design of the soft body, where the challenge was to bend over 180 degrees while maintaining stability during reconfiguration. The requirement of bending over 180 degrees arose from testing several methods for assembling the MODs. The functionality of such a structure must consider the specific behaviour of the robot, stability during assembly, and stability after the assembly. The MoleMODs presented here were prototypes for future professionally fabricated robots that would require stronger and more precise materials as well as sufficient electronics and control software.

The two main approaches were compared and their pros and cons discussed; both approaches are applicable to future similar investigations. Peristaltic motion is slow, but there is a lower chance that a robot will be damaged by imperfections in MODs. Cogwheels are fast and require more precision for the MODs; they are more easily damaged, but their movement is more precise and controllable than with peristaltic motion. Both options have advantages and disadvantages which should be considered based on a particular application.

Peristaltic Motion		Cogwheels	
+	-	+	-
Adaptivity	Speed	Speed	Low adaptivity
Fatigue strength	Pump and valves needed	Controllability	Easily damaged
Climbing	Precision	Discrete movement	Precision of MOD required
Strong fixation	Movement after assembly of MOD	Movement after assembly of MOD	Cog track needed
Flexibility		Precision	

Table 4. Advantages and disadvantages of movement of Mole

Important technical details of MoleMOD are compared in Table 4. The table describes all the experimental robot prototypes developed since the idea was introduced in 2016. The most successful versions, in the author’s opinion, are Versions 3 and 5.

		Passive part (MOD)							Active part (Mole)										
										Head				Soft Body					
Year	Version	ARCHITECTURE: **L** - Lattice, **C** - Chain, **F**-Freeform	CONNECTING MECHANISM BETWEEN MODULES: **Mech** - Mechanical, **Mag** - Magnetic, **No** Connection	CONNECTING GENDER: **G** - Gendered, **Gl** - Genderless	NUMBER OF INTERCONNECTING FACES	Weight (g)	SIZE (mm)	MATERIAL: **EPS** - Expanded polystyrene, **XPS** - Extruded polystyrene, **PLA** - Polyactic acid, **NFRP** - Natural fibre reinforced polymer, **CFRP** - Carbon fibre reinforced polymer, **Al** - Aluminium	MOBILE MOVEMENT: **PS** -Peristaltic Soft, **PH** -Peristaltic Hard, **R** -Ride(wheels)	FIXATION IN POSITION: **H** - Hard, **S** - Soft	REVOLVING OF HEAD	PREDOMINANT MATERIALITY OF HEAD: **H** - Hard, **S** - Soft	MATERIALS OF HEAD: **TPU** - Thermoplastic polyurethane, **PLA** - Polyactic acid	MATERIALITY OF SOFT BODY: **FS** - Fully soft, **SS** - Semi-soft, **HS** Hard&Soft	MATERIALS OF SOFT BODY: **TPU** - Thermoplastic polyurethane, **PLA** - Polyactic acid, **EPDM** - Ethylene propylene diene monomer rubber, **L** - Latex, **S** - Silicone, **PMMA** - Poly(methyl methacrylate)	EXTENSION	BENDING ANGLE	ACTUATION: **C** - Compression, **V** - Vacuum, **E** - Elastic potential energy	SIZE: Diameter x minimum length (mm)
2016	**0**	L	Mech	Gl	6,4,2	850	300x300x300	EPS	PH	H	Yes	H	PLA	HS	S,PLA	2x	45	C	110x200
2017	**1**	F,L	Mech	Gl	2	1050	400x150x150	PLA	PS	S	Yes	S	TPU,PLA	FS	S, TPU	2x	45	C	110x200
2017	**2**	*	*	*	*	*	*	*	PS	S	No	S	TPU,PLA	SS	L, TPU, PMMA	1.5x	45	C+E	145x250
2019	**3**	L	No	Gl	6	400	300x300x300	XPS	PS	S	No	S	TPU	FS	EPDM, TPU	3x	90	C+V	185x220
		C	Mech,Mag	G	2+2	750	185x185x555	PLA + NFRP											
		F	No	*	0	1300	2000x185	Al											
2019	**4**	C	Mag	Gl	2+4	210	135x135x135	PLA	R	H	No	H	PLA	FS	TPU	3.5x	180	C+V	115x260
2020	**5**	C	Mag	Gl	2+4	990	185x185x370	PLA	R	H	Yes	S,H	TPU,PLA	FS	TPU	4.5x	180	C+V	140x260
		C	Mag	Gl	2+1	200	200x200x200	EPS + CFRP											

Table 5. Characteristics of MoleMOD versions

Chapter 8.

SUMMARY

This thesis presented a framework for the design of reconfigurable modular building systems. Its focus was physical prototyping, through which the framework was constantly modified and improved. The approach investigated here focused on reducing the cost and weight of state-of-the-art modular robotic systems with an eye towards their application to architecture. This process culminated in development of a novel technological solution, sharing actuators within modular robots.

Chapter 1 introduced research goals and hypotheses and defined the methodology. From the beginning, it was clear that this dissertation would be focused on practical prototyping, through which the framework would gradually evolve.

Chapter 2 discussed the historical context of architectural development in the 20th and 21st centuries. The selected works, manifestos, and state-of-the-art projects—both historical and contemporary—showed that this dissertation and the concepts it examines are a natural extension of architectural changes which have been ongoing since the Industrial Revolution. The highlighted works did not illustrate one specific architectural approach, but rather provided a collection of diverse “hints” how architecture has progressed towards automated reconfigurability and adaptability through time.

Chapter 3 balanced definitions of design approaches and technical solutions. During the creation of prototypes, the author of this dissertation realized that the principles of self-assembly/organization can be observed in nature and that there is strong scientific background for this line of inquiry, especially in molecular self-assembly (e.g., folding of proteins, DNA). Observations about principles of robot behaviour were accompanied by an introduction to software and methods which could be adopted by architects. This chapter presents novel ideas to architects and provides a foundation upon which future development in this direction in architecture could proceed.

Chapter 4 focuses on technical solutions for state-of-the-art of distributed robot systems and made a unique evaluation of three groups of robots (modular reconfigurable robots, mobile assemblers, and mobile builders) regarding their potential for use in architecture. The systems presented represent diverse approaches which were considered by the author during experimenting and prototyping. Understanding these robotic systems is essential for future development on this field in architecture.

Chapter 5 was devoted to soft robots, an alternative to the classical “hard mechanism” robotic systems described in Chapter 4. Materials for soft actuators and their potential for use in architecture are described. Soft robotics principles were essential for the design of the sharable actuator for the MoleMOD prototypes.

In *Chapter 6,* a new strategy for the design of modular reconfigurable robots with sharable actuators is introduced and described. The method resulted from the research conducted for previous chapters and was essential for development of the MoleMOD system, a completely new system focused on architecture but applicable to different fields, including robotics.

Chapter 7, the experimental section, introduced 6 versions of MoleMOD robots and two main approaches (lattice and chain) for the assembly of modules. Experimentation through prototyping defined requirements towards simplification of the state-of-the-art reconfigurable modular MoleMOD robots.

8.1 Discussion of hypotheses and research goals

The goal of this dissertation was testing through experimentation with self-reconfigurable modular systems in order to investigate their possible usefulness in future architectural implementations.

Key hurdles which must be overcome in order to employ such systems in architecture at larger scales are their high cost and weight compared to traditional modular/discrete materials such as bricks, steel rods, and wooden boards. Sharing actuators provide a solution to this, and 6 prototypes were developed in order to create a framework for novel modular robotic system with sharable actuators to test this concept of making systems that are lighter and cheaper than current robotic systems. Versions 3 and 5 of the prototypes developed were most successful in this regard.

8.1.1 Answers to hypotheses

[H1] *“By sharing of actuators between individual modules, state-of-the-art modular robots can be made cheaper and lighter than current systems, while functionality remains the same.”*

It is obvious that by reducing the number of electromechanical parts with sharable robots that price and weight can be reduced, and this was confirmed by the equations presented in Chapter 6. However, an open question remains: can such robots can achieve reconfigurations similar to costly and heavy state-of-the-art reconfigurable modular robots?

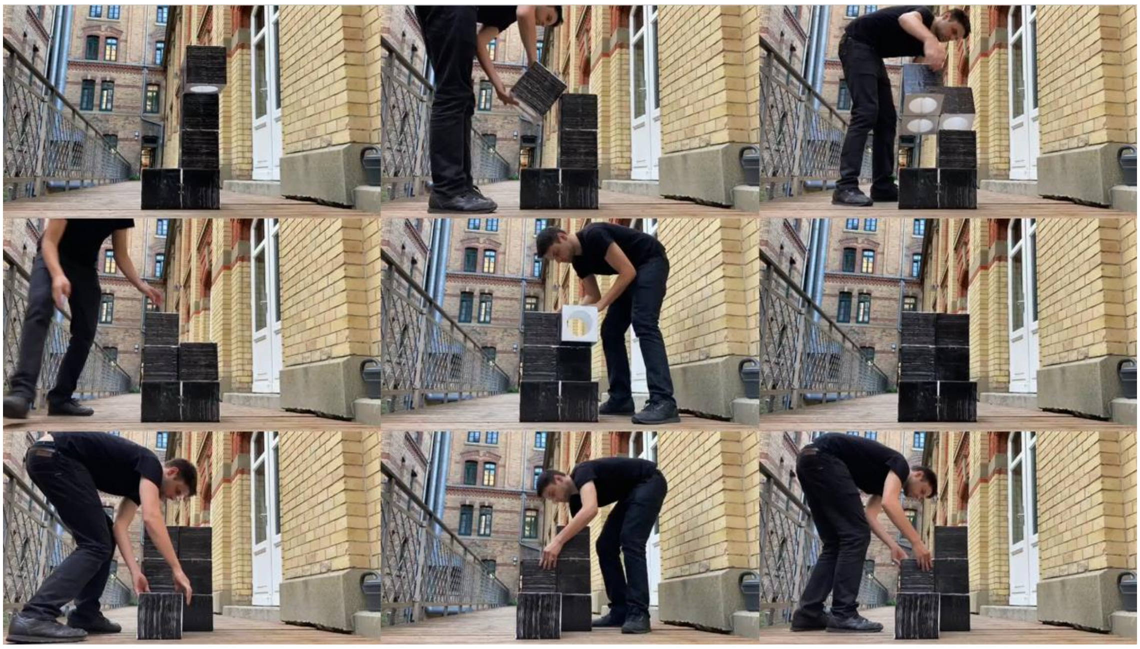


Fig. 77. Reconfiguration by two simple chains (each has 4 modules) (Version 5.b)

Reconfigurability "from inside" by a robot was demonstrated in Version 5 of MoleMOD. But this kind of reconfigurability is not applicable for all reconfigurable modular robot designs (Chapter 4). Reconfigurabilty possibilities are determined by the position of the axis of rotation (specified in Chapter 4), which should not be in the same direction as robot movement. Rather, the axis of rotation should be on one of the edge of a reconfigured module. Chain architecture is less universal than other architectures, but it is quite robust and, during MoleMOD prototyping, found to be more important than universality. Chain architecture is recommended for future implementations, since is quite safe and does not require complex robots.

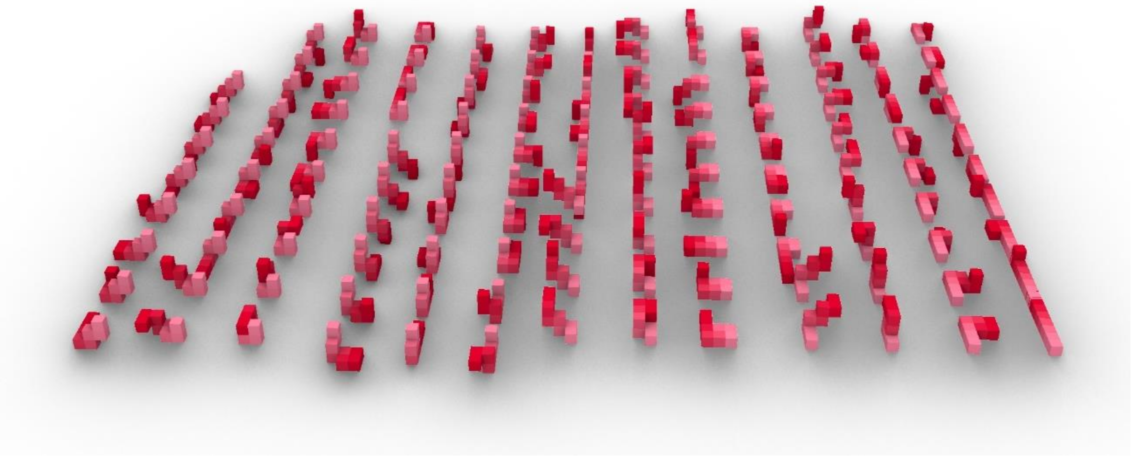


Fig. 78. Shows 128 possible reconfigurations which can be achieved by a chain consisting of 8 modules connected with a simple “hinge” on the interface between neighbouring modules.

[H2] *“Because reconfigurable modular robotic building systems facilitate reuse, the overall amount of materials, energy consumption, waste, and human resources used by the construction industry can be reduced if such systems are introduced in architecture.”*

[H3] *“Reconfigurable modular building systems can reduce requirements people demand for living spaces because reconfigurable living spaces can be modified to perform a variety of functions.“*

These two hypothesis are fused into one. H2 could not be fully explored in this dissertation since the material used has not yet been introduced on the market, but H2 can be fused with H3.

The modules (without robots) connected in a chain were tested for three days in daily home use. The modules were quickly adopted by users for different needs. Essentially, the modules adapted and modified the interior environments of users. Their simple design, lightness, and permanent interconnection allowed for universality and quick assembly. During experiments, modules were used for different functions, including being used as furniture. Such experiments showed reconfigurable systems hold potential for modifying space in different scenarios.

Fig. 79. Modification of space into different scenarios by two simple chains of passive modules (Version 5.b)

8.2 Applications

Even though this thesis focused on practical physical prototyping, some fundamental questions regarding the use of such systems have to been answered. While conducting research for this dissertation, the author had several discussions with individuals worldwide in which these individuals always expressed the same things: fascination with the novel technology and wondering how it might be used in real life.

The discussion below highlights different potential applications for reconfigurable modular systems.

8.2.1 Environmental change

The MoleMOD prototypes developed for this dissertation used a type of material which, in an ideal state of development, could be applied to almost any application. This material could be used at the nanoscale as well as on an architectural scale and incorporates scales comparable to building bricks.

A pilot application, the minimalization of occupied spaces, was addressed directly above. More broadly considered, the growing overall human population and the movement of people to cities is leading to greater numbers of living/working spaces needed. To reduce the size of living/working spaces together with energy consumption, this thesis introduced the concept of using adaptive reconfigurable systems in order to provide different functions for occupied spaces. Often, people occupy spaces that they do not use most of the time (e.g., bedrooms during a day, guest rooms during non-tourist months). As an alternative to such unused spaces, one space could be modified for different needs based on use requirements, as shown in Figure 80.

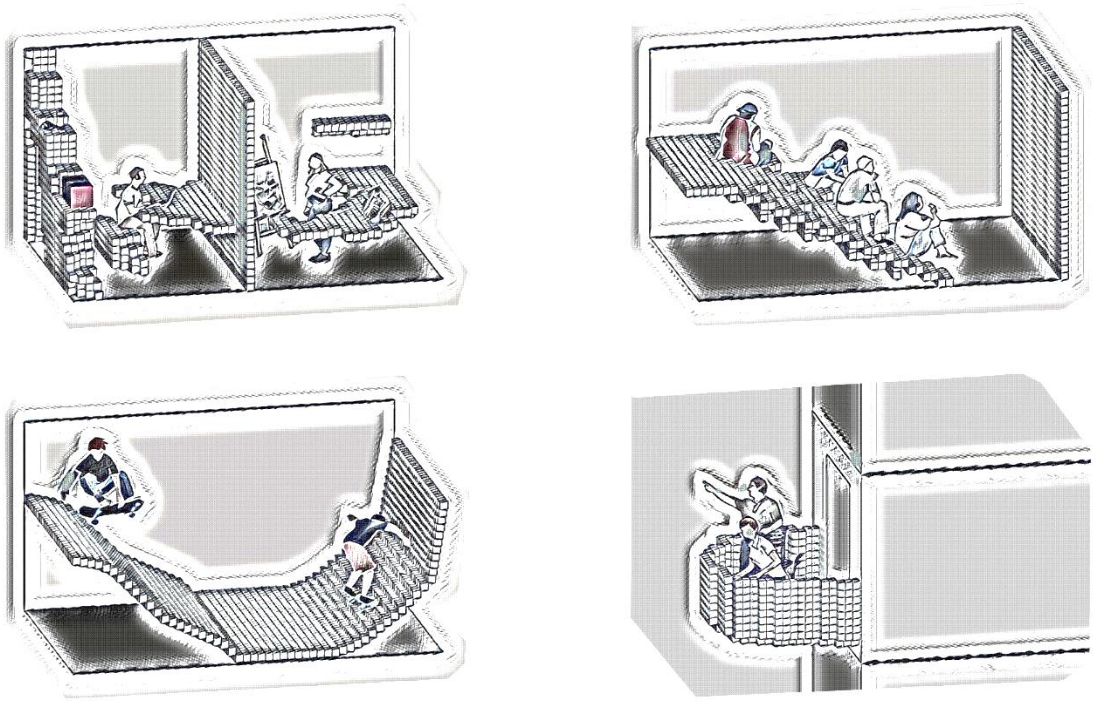


Fig. 80. Sketches of different scenarios for changing environments by using reconfigurable modular robotic systems.

8.2.2 Protection of people

The pandemic situation which arose during writing of this dissertation has highlighted a need for greater human protection. Simple tasks which can be done by robots should be done by robots, including the modification of spaces. In hospitals, for example, tasks like moving tables with food, building partitions between patients, and so on should be performed by sterile, intelligent reconfigurable materials/systems and not doctors and nurses, who should be employed for higher level functions.

8.2.3 Hard-to-reach places

Not all the spaces can be serviced by humans or they are dangerous. Autonomous reconfigurable modular building systems can be used in such cases.

8.3 Remarks and implications

8.3.1 Discretization of configuration

When using chain systems, the author suggests working with predefined configurations which are later combined. This reduces computational time when compared to an “endless” chain of modules. Discretization into several smaller chains reduces requirements on joints, which transforms forces from a lower number of modules.

8.3.2 Reconfiguration by humans

Reconfigurable robot systems use specific types of interconnection and reconfigurability mechanisms. These are controlled by electromechanical parts, which make overall systems expensive and complex. Working with sharable actuator in the context of MoleMOD taught us modules can be simplified into basic reconfigurable principles which are serviced by a mobile actuator. Such actuators could be completely replaced and humans could perform reconfiguration tasks, as illustrated in Figure 81.

8.3.3 Assembly as in a game

This idea stems from protein folding concepts. Researchers have investigated methods for solving the process of protein folding in game form (Section 3.1.2). This concept could be applied into the MoleMOD system, with the complex process of assembly being solved not by computers but rather by people playing a game.

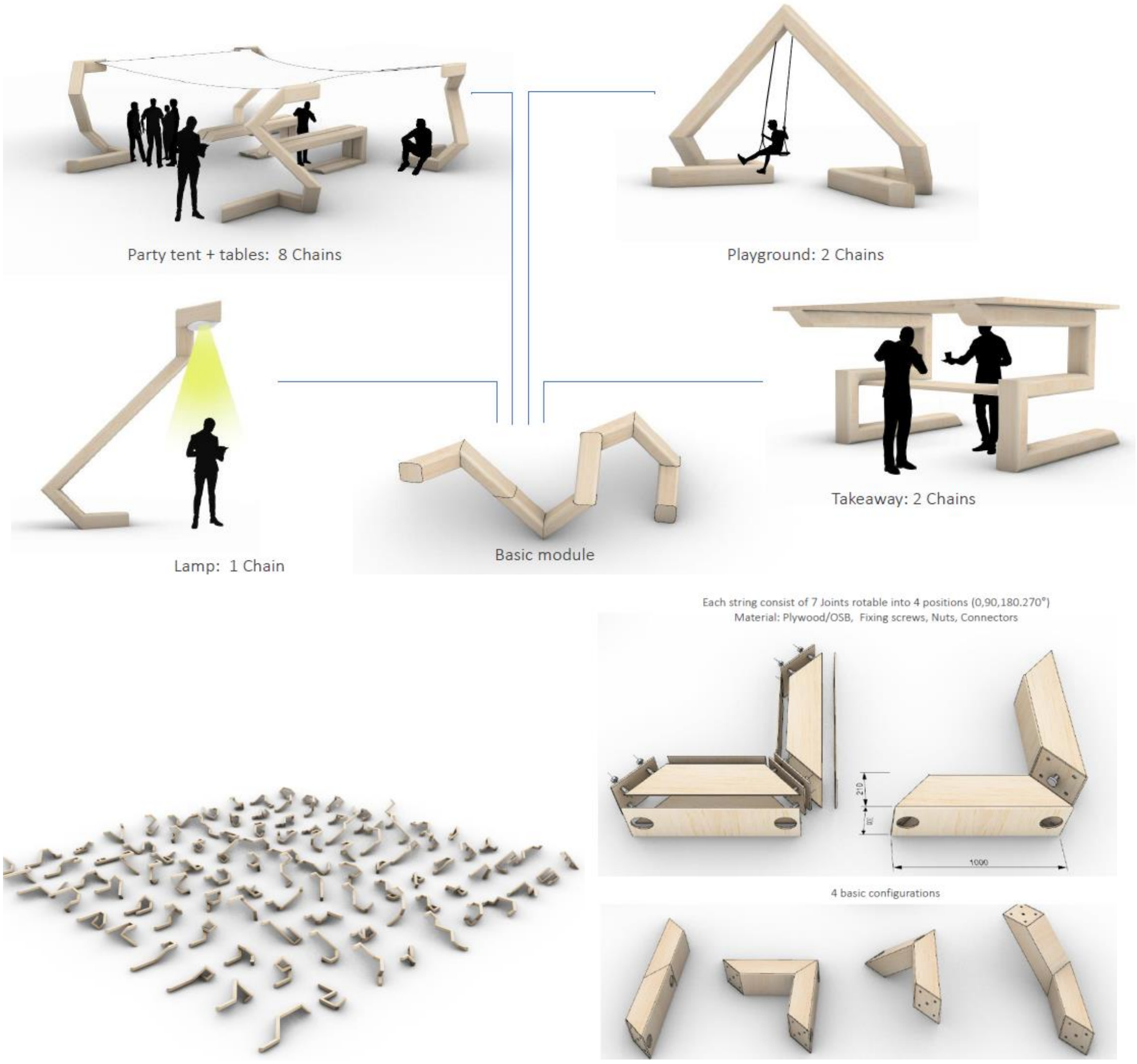


Fig. 81. The human reconfiguration concept was used to design a universal modular installation for the Floating Man music festival in Serbia, originally slated to be held in Summer 2020. The goal was to analyse how people would reconfigure modular blocks connected in a chain structure. Unfortunately, the installation was postponed due uncertain reasons to a date following submission of this thesis.

8.4 Future development

The discussion of future development is divided into three parts: Reconfigurable systems, Active part of MoleMOD. and Passive part of MoleMOD.

8.4.1 Reconfigurable systems

Reconfigurable systems in general should start moving from the laboratory to the larger scale. More than 30 years of development have not yet resulted in stable industrial applications, largely because of high costs and the complexity of control mechanisms, as discussed above. Future investigation and development should be aimed at solving fundamental questions surrounding applications, price, robustness, and safety. For architecture, crucial questions include how such discrete systems should deal with the continuous elements used in buildings (e.g., piping, glass thermoinsulation) and materials used for their continuous shapes. A key task is figuring out how these materials can be discretized to enable the same functions. Systems which should be investigated more are those which self-replicate and assemble themselves into functional machines that can be also be used during an initial building process

8.4.2 Active part of MoleMOD

Experiments with MoleMOD were based on electromechanical devices such as solenoids, pumps, and wires which powered and controlled soft actuators. Future investigations should replace such devices with smart materials which are adaptive, responsive, and safe. Robots of the future should more closely resemble living organisms controlled by artificial intelligence or environment stimuli. The active part of such systems can be created in different scales and for different functions. In addition to reconfiguration, active parts could potentially be used for distributing things or even people around a building, if one imagines a multidirectional elevator.

8.4.3 Passive part of MoleMOD

For future systems, new materials that are light and safe for people, animals, and things should be investigated. Modules should be created in different dimensions and with different materials and their combinations could thus result in complex discrete structures with functionally oriented distribution of materials. Module surface could be covered by technologies for renewable energy harvesting. Materials should be also ecological and have the ability to be precisely fabricated.

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