From MoleMOD to MoleSTRING

Design of self-assembly structures actuated by shareable soft robots

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This paper proposes a self-assembling system for architectural application. It is a reaction to current building crisis and high energy consumption by building industry. This Unique system is based on a reconfiguration of passive elements by low-cost soft robots able to move inside as well as configure them into 2D/3D structures similar to recent Modular robots. A goal is to significantly reduce the high price and complexity of state of the art modular robots by minimization of mechatronic parts and using soft materials. The concept focuses on life-cycle management when one system can achieve assembly, reconfiguration, and disassembly with a minimum of waste. The paper compares three different versions of a self-assembly system called MoleMOD: MoleCUBE, MoleCHAIN, and MoleSTRING.

Keywords: *Self-assembly, Soft robotics, Modular robotics, Reconfigurable string, Adaptive architecture*

INTRODUCTION

Constantly changing society and human capabilities evoke that architecture should participate. The changes are still faster, and it is difficult to predict if the buildings built today will meet with future requirements. Since 1990 the building industry is stagnating and not able to meet all the building requirements in time. Adaptation of principles of the 4th industrial revolution is much slower than in the other sectors. More than 40 % of global resources and energy consumption is the evident sign that building approach should be changed. Usage of self-assembly adaptive robotic systems can significantly reduce currently missing human resources and can be useful in a situation when the reduction of risk related to human danger (Melenbrink et al., 2017) conditions are necessary. A building made by self-assembly systems can enable construction to be responsive to current conditions and decisions, what will make a building life cycle ongoing instead of fixed to several stages (conception, design, procurement construction, use, demolition, etc.) Adaptivity

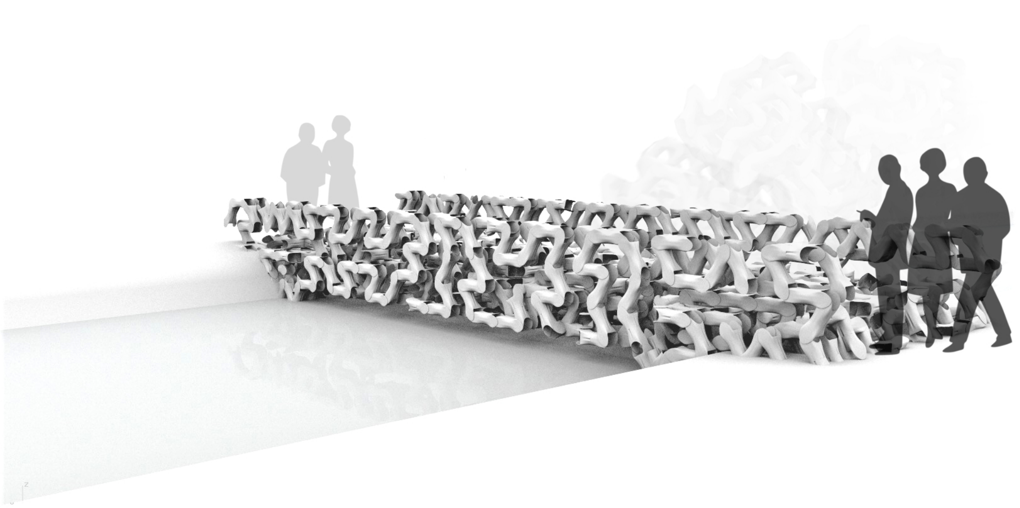

Figure 1
Illustration of a possible application of MoleMOD (MoleCHAIN) in a form of self-assembly bridge

of such systems will reduce the amount of energy and other resources needed for renovations or demolitions. Those are some of the reasons why research architects introduce architecture consists of interacting agents(Spyropoulos, 2016) in different forms and scales capable to adapt buildings to certain needs for all its life cycle (FIg. 1) We do not expect that the whole building will reconfigure every minute into the new shape. But thanks to a smart adaptive concept one building system can supply all the modifications during its life cycle (assembly, reconfiguration, and disassembly)(Dahy, 2019). In combination with sustainable materials and renewable energy, it should significantly reduce energy consumption and the amount of waste from the building industry. This paper focuses on the construction of sharable soft robot concept Originally called MoleMOD (Petrs et al., 2017) significant by a symbiosis of Active part in form of the soft robot and passive part of variety geometries: Cubic Modules, Chain Modules or Strings, Also so-called MoleCUBE, MoleCHAIN or MoleSTRING. The paper describes in detail the construction of the soft robot and discusses its integration to 3 different passive part approaches.

SELF-ASSEMBLY AS A BUILDING TECHNIQUE

The recent rise of distributed systems sparked our interest in their physical application in the form of self-assemble building material (Tibbits and Cheung, 2012). Work is highly influenced by recent research in a field of modular robotics (MRS) (Ahmadzadeh, Masehian, and Asadpour, 2016). MRS can achieve almost any shape by self-reconfiguration of its modules. From a 1957 when the British mathematician Lionel Penrose first introduced a concept of self-reproducing wooden blocks and 1988 when the first modular robot "CEBOT" was presented by Toshio Fukuda lot of modular robots have been already developed (M-Tran, MoleCube, Roombot, Atron,etc) but mostly for a smaller scale without any exact application (Ahmadzadeh, Masehian and Asadpour, 2016). In the last years, MRS have influenced also architecture especially as a part of academic projects unfortunately without any really used application. The reasons are usually the high price and complexity of the system. Especially the price can be reduced by a number of mechatronic parts usually installed in every single module. Near the exception may be a project Termes (Petersen, Nagpal and Werfel, 2011)from Wyss Institute consists of modules manipulated by few cooperative mobile robots into a lattice structure or climbing robots (Melenbrink et al., 2017)where rods are manipulated by climbing robots into a triangular lattice structure. In both examples, the number of robots is significantly smaller than a number of manipulated elements. On the other hand, these two examples are rather Mobile than Modular, because the active part is placed outside the manipulated module.

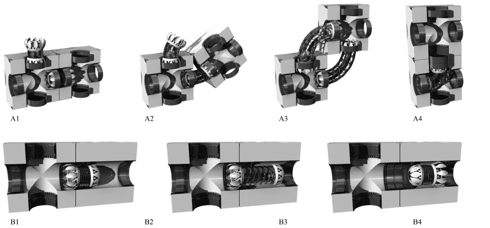

Figure 2
Lifting and movement inside MoleCUBE concept (Original concept 2017 with integrated thread connecting system)

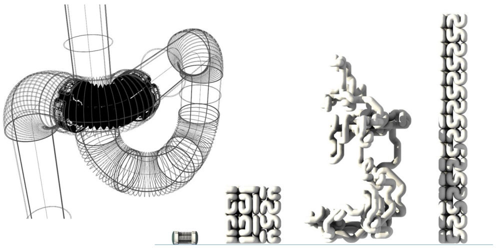

Figure 3
MoleSTRING A. movement inside of shapeable String B. Illustration of possible transformation of String into the column

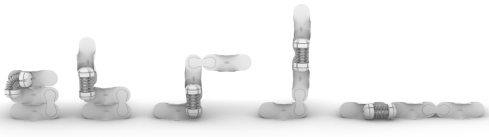

Figure 4
The 3D section of possible reconfiguration of MoleCHAIN

MOLEMOD FAMILY OF SHARABLE MODULAR ROBOTS

The unique concept called MoleMOD has investigated the possibilities of self-assembly by sharable mechatronic parts in between the lightweight modules from inside. Compare to the state of the art modular robots this was found as a suitable solution for self-assembly systems in architecture. The major advantage is the elimination of the necessity to have every element fully mechanized what positively influences the control complexity, weight, and especially price. The concept coming from application the field of modular robotics is usually concern as a real-time assembly where several modules have to be performed at once and relatively fast to solve tasks like crawling, climbing, fixing, etc. On the other hand, most of the architectural purposes do not need to be permanently configured what enables to work with slower assembly and configurations. Therefore MoleMOD is developed as a system with a minimum number of active mechatronic parts it allows also to integrate a very high number of mechanized elements in case the increase of speed process is needed.

Original MoleMOD concept also so-called MoleCUBE(FIg. 2), MoleSTRING (FIg. 3) or MoleCHAIN (FIg. 4) is based on sharing of active parts in the form of soft robots in between passive Modules. The split gave a name to an entire system, which is a join of “Mole” represents the active part and “MOD, CHAIN, STRING” represents the passive part. The Moles can be sharable and only if it is necessary, they come to a destined place, fix and reconfigure the MODs to purposed shape. A novel is a movement of manipulating robots inside the structure with two general advantages: 1, Robots are protected by the structure against outside unpredictable aspects like weather animals, etc. 2, robots do not limit the structure shape by their operating space. In recent MoleMOD versions, regular 3D lattice system was used for passive blocks, what was found problematic. For the durable lattice-based system is a strong connection between the modules crucial. The most commonly used are latch-catch systems or magnets. From a structural view, the connections are the weakest points in structure what in combinations with high requirements on robot precision makes the system very complex. To simplify entire system 3D based lattice is replaced by chain based architecture

Figure 5
Mole comparison of its minimum and maximum stretchability

tab. 1 Strings or chains can be configured to space-filling curves and intertwine itself to a solid structure. The essential ability to attach and detach from the other modules becomes secondary (Cheung et al., 2011).

MOLE - ACTIVE SOFT ROBOTIC PART

The goal is to develop a robot with a minimum number of mechatronized parts and sensors which easily adapts to passive elements in a sense of soft robotics (Seok et al., 2013). Therefore one of the major advantage of "Mole" is the movement in a predictable environment the flexibility of the robot is an advantage. Moles have two main functions: peristaltic movement (Seok et al., 2013) (FIg. 5, 12)inside the MODs and manipulation with MODs. Thanks to the universality of its soft body those two functions don't need to be separated for instance in the form of wheels and arms. Moles consist of two primary components: a soft body and heads attached to both soft body end (FIg. 6). Each head has four inflatable pillows placed on an outside diameter of the head which stabilize robot in passive part by pressure on its inner surfaces. The body connects both heads by four pneumatic bellows controlled by pressure and vacuum. Bellows can be bent into four possible directions as well as to be stretched during the peristaltic motion. Soft robotic principles (Paik, 2015) minimize the number of sensors and allow the better adaptivity to a surrounded environment in a sense of living organisms.

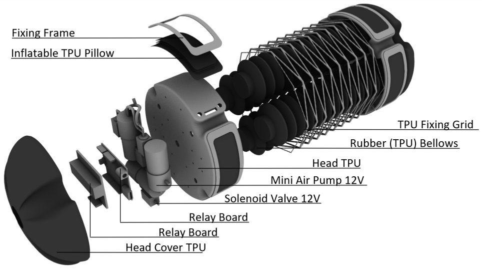

Figure 6
Mole components

Bellows

The four rubber bellows are placed in between the heads. By controlled changing between pressure and vacuum, the bellows are able to stretch, squeeze and bent. The range of stretchability is in between 6cm when a vacuum is applied and 38 cm when overpressure is applied. By the combination of pressure and vacuum is the soft body kept stable and able to operate with higher loads needed for the transformation of passive MODs CHAINs, STRINGs, etc. The vacuum and pressure loads work in the opposite direction what makes the soft body stable without the need of opposite forces provided by other devices or materials. The vacuum can provide very strong stabilization what makes the robot almost rigid. The used bellows are fabricated from EPDM Rubber closed with EPDM rubber cap with input for air supply(FIg. 7). Those bellows can be also 3D printed by a similar method as pillows(FIg. 8). In this stage, they were not 3d printed because of long printing time. By the 3D printing method, the weight of the robot can be reduced because of the minimalization of heavy rubber parts.

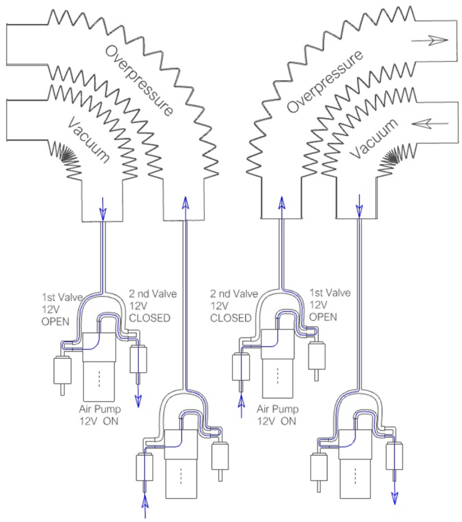

Figure 7
Section of bellow bending (Soft body) with air control (pressure, vacuum) by air pumps and solenoid valves.

Figure 8
A. Sliced 3D model in Ultimaker Cura Software B. Deflated and Inflated 3D printed Pillow

Pillows
Pillows are completely 3d-printed from a flexible filament, inflated by a 12V air pump and controlled by one 12V solenoid valve(FIg. 8). For the pillows FDM 3D printer Ultimaker 3 with two printing heads was used, Two heads allow to print two materials in parallel what is necessary for the inside of the pillow which needs to be filled during the printing by washable material (PVA, Hips, etc.). For the Pillows was used Ultimaker TPU 95a flexible filament for the support washable Ultimaker PVA filament. The final 3d printed piece is only 1.6 mm height consists of 16 x 0.1 mm layers of TPU and PVA in order to allow a folding effect. Pillow expands when air pressure is applied up to 30 mm with maximum pressure 3 Bars. Compare to pneumatic actuators which often deal with the problem of how to connect them to air supply without leakage the 3d printed actuators allows printing various shapes wit already integrated inputs.

Head and caps
The geometry of the head is designed according to the inner surfaces of the passive part and bellows on the outside. The head fixes the bellows together and provides the outer surface for four inflatable pillows. Each head has four grooves allow to follow a negative track placed in the inner surface of CHAIN or MOD (STRING). In between the Cap and Head is placed necessary electronics like pumps, valves alternatively sensors, relay board, Arduino, breadboards, etc. Both components are also printed from Ultimaker TPU 95a flexible filament what allows certain flexibility for the operating.

Electronics and control.
The distribution of air is provided by opening/closing of Mini-solenoid 12V valves and Pumps. For each bellow one pump and two valves are used. The valves and pumps are controlled by relay board, the pumps and valves for pillows are controlled by mosfets TIP 120. The signal to Relay board or transistor coming from Arduino Uno board operated currently by KeyPad. The firmware was developed in Arduino IDE. In the future, the autonomous system will be applied as well as pressure or position sensors.

CUBE, CHAIN, STRING - PASSIVE PART
SInce MoleMOD was firstly introduced (Petrs et al., 2017) three major passive elements were developed: Cube, Chain, and String. The passive elements are crucial for the final design of the structure as well as for its assembly. This part investigates them through their characterization and integration with Mole tries

to get comparative results for future development.

MoleCUBE

MoleCUBE is the original MoleMOD concept using regular lattice-based architecture(Brejchova et al., 2017)) consisting of cubic passive elements where each cube has minimum one tunnel where Moles operate. The original cubic shape of passive blocks was chosen since it is mostly used in modular robotics (Ahmadzadeh et al. 2016). However, the system is not restricted only to cubic block shape alone. It can consist of arbitrary polytopes possible to build conglomerates without extensive limitation. The MoleCUBE can provide a variety of shapes in a way of voxelization of certain space. This allows faster assembly and less complexity than the chain Geometry. On the other hand, the high number of connections is needed with a high emphasis on their precision and function. The tested piece can be easily fabricated by milling of foam or other lightweight material. For MoleCUBE Styrodur foam was used (FIg. 9).

MoleCHAIN

This concept is designed as a 1D Structure with chain architecture able to fill only the 2D space. The concept is based on classical chain modular robots like Superbot (Salemi et al., 2006) or M-TRAN (Kamimura et. al., 2002). Contrary to those two robots MoleCHAIN has only 1 degree of freedom because the rotation along the main chain axis is not considered. The chain system was designed as the most simple solution to build 2D structures. The entire chain consists of 2 links: main inner link and secondary outer one connecting the main link. The weakest point is the connection between the chains. The links allow rotation like in classical bike chain, the problem is how to fix the rotation to a certain position. This is currently provided by friction in between the links. The chain prototypes were fabricated by natural Fiber winding method use flax fibers/tapes(FIg. 10). It demonstrates the high variety of material solutions includes also natural materials (Dahy, 2017) what is within MRS unique.

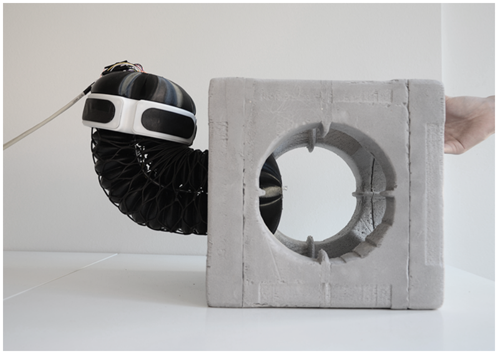

Figure 9
MoleCUBE

Figure 10
MoleCHAIN

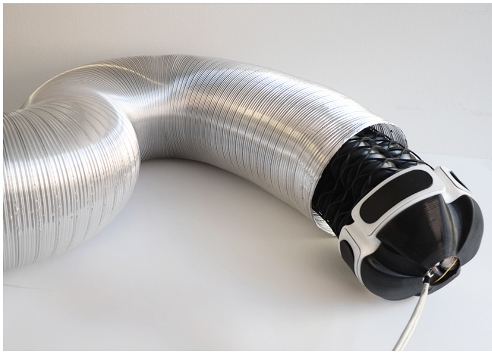

Figure 11
MoleSTRING

MoleSTRING

Not only the Mole can be considered as a soft but also the final string structure. No matter if MODs are from soft or rigid materials. The entire structure consists of multiple DoF able to adapt to different morphologies as an extrinsic softness (Paik, 2015). The assembly and folding principles are based on recent research in fields like protein folding or space-filling curves. Several technics was already developed for instance: Hamiltonian Circuit, Reverse explosion, Hilbert or Peano curve (Cheung et al., 2011). Etc. The choice of the material depends on the target application but for the prototype, an aluminum tube was chosen because of easy shaping and weight(Fig.11). The string concept has the main advantage in DoF which is almost infinite. This allows a variety of shapes not defined by any regular lattice. The concept allows better adaptivity to environment closer to soft robots on the other it is more difficult to exactly control the position of the String.

Characterization

The Passive part (MOD) is essential for a specification of the system architecture. In this paragraph, we compare three different architectures represented by MoleMOD (table 1). The comparison is based on MITE framework characterizing Modular Robots (Ahmadzadeh, Masehian and Asadpour, 2016).

Architecture. The architecture is generally classified into several groups by the arrangement of the unit. The most used are Lattice, Chain, Truss, Hybrid or Mobile Architecture. Therefore, an active part is moving inside the passive one and reconfigures them, the MoleMOD family is not considered as a mobile architecture but as a lattice or chain according to the arrangement of the passive parts. The lattice architecture consists of independent cells occupy 3D or 2D lattice for the movement the assistance of neighboring cells is necessary. The lattice system is more versatile than the chain system, on the other hand, it has higher requirements to connections and the final structure is highly defined by a used grid in a way of voxels. Chain architecture doesn't offer such a versatility like a lattice, on the other hand, the problematic connections are particularly replaced by permanent joint.

Connection. The connection is the most critical part of the modular robot. The complexity of connection and their structural properties are one of the reasons why modular robots are not used as large scale structures. The most used are Mechanical (for example latch-catch systems) and Magnetic connections. The goal of the MoleMOD is to completely avoid active mechanical connections and generally simplify them as in case of MoleSTRING when the shapeable aluminum tube is used.

Contact faces. Contact faces define how many faces can be potentially faced in between two cells (passive part).

Structure. Defines the displacement of cells. There are three possible displacements Linear (1D) Planar (2D) and Spatial (3D). The structure is defined by displacement not by space filling it means that the 3D space is possible also to reach for instance with 1D structure as in case of MoleSTRING. The space possibilities are defined in Table 1. by row called space.

Degrees of Freedom. In the MRS DoF specifies independent displacement or aspects of motion. In MRS the rotation is mostly used except Truss architecture where only linear movement is used. The DoF are considered to one module, not to entire conglomeration where it depends on a number of cells.

Table 1
The table compares 3D different MoleMOD systems regarding to MITE framework for Modular robots

	MoleCUBE	MoleCHAIN	MoleSTRING
Architecture	Lattice	Chain	Chain
Connection	Mechanical /magnetic	Mechanical/magnetic	No connection /folding
Contact Faces	6	4	∞
Structure	1D, 2D, 3D	1D	1D
DoF	2	1	∞
Tested Material	Styrofoam	Bio-composite	Aluminum
Space	3D	2D	3D

Testing

Each of three different passive elements was tested according to its interaction with Mole. Several tasks were chosen to provide guidance for the future development of MoleMOD.

Movement. It shows an ability of Mole to move inside of the MOD to a certain position.

- MoleCUBE: Potentially can move inside smoothly if the distribution of the air is smartly controlled to protect the Mole leave the virtual track in a place where three holes are meeting. For the smooth movement, the friction in between Mole and MOD should be increased
- MoleCHAIN: The geometry of chain doesn't allow the proper movement in the connection part because of big distance in between pillows and inner surface of MOD . The movement in "tunnel" part of the chain works sufficiently.
- MoleSTRING: Movement inside of the String works from all the three prototypes as the best. It is highly recommended to cover inner surface with materials like silicone to allow smoother movement. Advantage of the string is the completely closed surface.

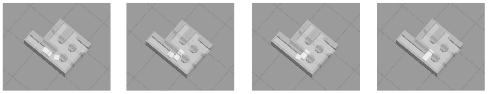

Figure 12
Movement of Mole inside MoleCUBE in Simulator Gazebo (Brejchová, 2019)

Figure 13
Mole configurations

Fixation. It tests the strongest of fixation to an inner surface of MOD to protect the Mole against any movement, its accuracy, and speed of fixation.

- MoleCUBE: To different parts are considered. Fixation to outside "wall" of the cube works very well because the geometry of the surface follows the shape of the robot very precisely. The middle part is problematic because the pillows cannot reach the inner surface.
- MoleCHAIN: Similar to its movement, the robot cannot be fixed properly because of the high inaccuracy in the connection part. Fixation in "tunnel" part works sufficiently.
- MoleSTRING: Fixation is satisfactory, but when higher loads are applied the fixation can release

Stuck inside. This important test says how big is the change that Mole can get stuck inside the structure and it is visual control.

- MoleCUBE: Stuck robot can be easily removed through another hole in the CUBE.
- MoleCHAIN: Regarding low accuracy, in the connection part, the stuck ability is relatively low. Thanks to a high number of openings the robot can be visually controlled
- MoleSTRING: Regarding a completely closed surface the robot cannot be visually controlled and a stuck robot is difficult to remove.

Lifting. It describes how easily the MODs can be lifted by Mole

- MoleCUBE: The lifting is possible regarding the good fixation. The problem is to keep the lifted element revolving around one axis.
- MoleCHAIN: The lifting was not possible to test because the robot can't be fixed in the part where two neighbor links are meeting.
- MoleSTRING: In this case, moleMOD is not lifting but more it is bending the string. Due to low visibility inside the string, it is difficult to provide this test properly.

APPLICATION

In general, MRS allows a high range of possible applications. In fact, it is a molecular architecture from which almost anything can be built. Applications are affected mostly by a scale of the used modules. A range of the scale can start from nanoparticles used for example in medicine to superstructures where one module can be for instance one apartment. In our case outside diameter of Mole is 180 mm what gives approximate dimensions of MODs. Although the research is a reaction to current building crisis, still there is a long way to fulfill all the needs for functional houses. Currently, we focus on reusable and temporary building structures out of one material without embedded technologies. For instance, fair trade stands are usually used once and destroyed, or one design is used for many years. Both can be replaced by a self-assembly system that can look at every show differently what will reduce costs for human resources and make the stand design non-repetitive. During the building process different secondary reusable structures like formworks or scaffolding takes a place, the number of resources can be reduced by reusable autonomous self-assembly systems. Use of MoleMOD can give a sense of security in places where there may be low safety of workers. In a situation like a forest fire, flooding or landslide it can be found useful for quick fixation of a certain problem. Mole by itself can be also used for inspection of different piping as well as a part of building infrastructure. The universal concepts allow using the Mole for different transformations of building elements, for example, facade systems

CONCLUSION AND FUTURE WORK

It is important to consider this research as a completely new field when the compliant soft robotic principles are integrated into complex MRS logic. The last version of MoleMOD extends recent versions by next two approaches when regular lattice grid is replaced by a chain. Discussed tests gave important information regarding the interaction of Mole and MOD. As the most perspective seems to be concept MoleSTRING, however, several improvements have to be done for instance surface transparency to visually control the robot. As the less sufficient was evaluated concept MoleCHAIN when basic geometrical requirements don't allow to proper movement of Mole inside of the structure. On the other hand, using of Biomaterials is appreciated. The step back seems to be concept MoleCUBE but the characterization and tests surprised especially because of the control complexity and good fixation on the "wall" part of Cube. A disadvantage is a movement across the crossing of tunnels and connection between elements. It is not possible to exactly select one concept and continues. From all of them, particular knowledge will be taken. All the concepts are currently dealing with high friction what was not considered before, this will be improved through used surface materials allow the smooth movement. We will also continue with a weight reduction of Mole for example by 3d printed flexible elements as in case of the pillows. In the early future, the MOD will be optimized regarding the results provided by this paper. In later stages, the assembly planning will be tested according to structural and geometrical conditions during and after the building process. The main goal of the research is a cost reduction of state of the art MRS and their use for architectural activities as an alternative technic for 4th industrial age strategies.

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