



FIG. 1 CONCEPTUAL 3D RENDERING OF BASIC BODY PLANS: FROM UPPER LEFT TO LOWER RIGHT: BPA; BPB1,2,3; BPC1,2,3 AND BPD

SL. 1. KONCEPTUALNI PROSTORNI PRIKAZ OSNOVNIH TJELESNIH NACRTA: ODOZGO LIJEVO PREMA DOLJE DESNO: TIP A; TIP B1,2,3; TIP C1,2,3 I TIP D



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BASIC BODY PLANS FOR SOFT MODULAR PNEUBOTICS IN ARCHITECTURE

OSNOVNI TJELESNI NACRTI ZA MEKANE MODULARNE PNEUBOTSKE KONSTRUKCIJE U ARHITEKTURI

ADAPTABLE AND RESPONSIVE STRUCTURES
BIOMIMETICS
BODY PLAN
PNEUBOTICS
SOFT ARCHITECTURE

PRILAGODLJIVE I REAGIRAJUĆE KONSTRUKCIJE
BIOMIMETIKA
TJELESNI NACRT
PNEUBOTIKA
MEKI ROBOTI

This article introduces a theoretical model for the design of pneubotic structures that can be constructed and actuated by using the modular unit volume element. Through analysis of construction of soft robots, pneumatically adaptive and responsive structures and art installations, a set of four basic body plans is proposed, as abstract expressions that form a base for the design of soft modular pneubotics in architecture.

Članak donosi teorijski model za projektiranje mekih pneubotskih konstrukcija koje se mogu konstruirati i pokretati koristeći jedinični modularni volumenski element. Analizom konstrukcije mekih robota, pneumatski prilagodljivih i reagirajućih konstrukcija te umjetničkih instalacija, dobiven je set od četiriju osnovnih tipova tjelesnih nacrti kao apstraktnih izraza za projektiranje složenih modularnih pneubotskih konstrukcija u arhitekturi.

INTRODUCTION

UVOD

Biomimetic pnebotic structures in architecture¹ are pneumatically responsive and adaptable structures still in early development that follow the development of soft robots. Unlike the more widely spread hard robots, whose parts are made of rigid materials and whose movements are mechanical, soft robots are made of elastic materials that mimic the structure and movement of soft body organisms. Soft pnebotics can be regarded as a recent invention, although some examples of soft pneumatic automata existed before the digital era and some hard air-run automata also existed in the 19th century. The majority of recent pnebotics in architecture mostly use linear pneumatic actuators, be it hard air cylinders or soft artificial muscles, and less often volume elements to actuate the structure. Their morphodynamics range from very fast movements and drastic transformation like those in *Tower 2* structure from Hyperbody Group² to smaller changes like the ones used in the adaptable 375 m² pavilion for temporary exhibitions *Airtecture* form Festo tested in Germany.³ Less often are those structures soft in both their key segments – their construction and actuation elements. With all their components and performance, pnebotic structures often appear as artificial bodies similar to living beings.

The idea of a “body” is already present in the field of soft robotics, as well as in art installations and adaptive and responsive architecture. It is often used to describe a part or a

whole structure. Lipson Hod for instance, in his research on evolutionary technics of developing robotic controllers, uses the terms *morphology* – for physical structure, and *controller*, for a “separate unit that governs the behaviour of the morphology”, in control theory also called plant and the control, to describe the *body* and the *brains* of robots.⁴ In computer sciences, terms borrowed from biology like *genotype* and *phenotype* are often used to describe the generative procedure and resulting finite digital representation respectively. Karl Sims uses directed graphs (*genotypes*) to generate bodies of virtual creatures (*phenotypes*) as “a hierarchy of articulated three-dimensional rigid parts”.⁵ He also uses anthropomorphic terms like “body”, “leg segment” or “limb segment”, or else “brain” to describe the structure and logics of evolving virtual creatures in simulated physical environments.⁶ On the topic of new problems regarding design of soft robots, Iida and Laschi suggest novel approaches to complex simulations of soft robotic bodies and sensory-motor processes allowing for body-control co-optimisation.⁷ The research in architectural robotics is thus conducted on the level of the body and of computer control – as a sort of artificial intelligence of the structure.

Although soft robots are more complex to simulate, they are in fact less complex (and cheaper) to produce and easier to interact with users and the environment, due to their softness and (body/material) compliance⁸ which makes them less prone to damage and less likely to hurt users unlike hard robots.

Marchese, Önal and Rus use the term *continuum body* to describe parts of a *fish robot* that has actuation part constructed as one continuous element with built-in “spine” and expandable sides with embedded *pneumatic network*⁹, instead of a series of parts typical for hard robot structures.¹⁰

Many other authors also use the expression “soft body” when describing soft robotic structure. Wever even calls a pneumatic cushion of otherwise nonrobotic tensairity structures “a pneumatic body”.¹¹ Describing classical robotic bodies, some authors use expression like “robots having hard body plan”¹², further differentiating soft from hard robots.

THE THEORETICAL CONTEXT OF A “BODY”

TEORIJSKI KONTEKST „TIJELA”

The French philosopher Gilles Deleuze describes a “body” through terms of longitude and latitude. It can be anything that has these properties. A body “[...] can be an animal, a body of sounds, a mind or an idea; it

can be a linguistic corpus, a social body, a collectivity. We call longitude of a body the set relations [...] that is between *unformed elements*. We call latitude the set of affects that occupy a body at each moment, that is, the intensive states of an anonymous force. The longitudes and latitudes together consist Nature [...] which is always variable and is constantly being altered, composed and re-composed [...].¹³ Regarding modularity and reconfigurability, Hod Lipson states: “Reconfigurable robots are composed of many modules that can be connected, disconnected and rearranged in various topologies to create machines with variable body plans. Self-reconfigurable robots are able to rearrange their own morphology, and thus adapt in physical reality”.¹⁴

Applied to architectural structures, the longitudes of their bodies are their material, structural and geometric properties, while their latitudes are their physical, static, dynamic, user-induced or other influences. Dynamically adaptable structures thus expand their longitudes to a greater span of properties like motion, physical properties, changing geometries and disposition of elements in order to better relate to their latitudes, their capacities being actualised more frequently. Structural body as a machine or a swarm of machines is a structure that can produce an effect of change in its longitude in accordance to the change in its latitudes, but can also exist in relation to much greater latitudes. Compared to a notion of society and networks, Deleuze and Guattari connect “[...] large-scale networks with the networks in the body, and between bodies, so that we start to see things like temperament and identity as emergent properties that are products of the machines immanent in the initial conditions”¹⁵.

Kaas Oosterhuis and associates, in a trans-disciplinary research project Hyperbody, expand the idea of a body to a *hyperbody*, i.e., a body that contains a computer code. Hyperbody is thus an informationally permiated body – a robotic structure capable of executing the code and reacting within longitudes and latitudes of the field of its possibilities. In this manner, the new term can describe complex relations within the structure and within the context. Citing the research group Hyperbody, Gruber relays that “Hyperbodies are pro-active building bodies acting in a changing environment”¹⁶, and Bier explains: “A hyperbody is to architecture what hypertext is to literature. [...] A single computer is worthless in many ways. [...] An isolated building has no importance whatsoever. Only by virtue of its relations to its users and other built bodies, buildings literally build up meanings in our lives. I see hyperbodies as the ultimate form of relational building bodies.”¹⁷

Structure thus becomes “living formation” that reacts and learns, and, if networked with other bodies, it can exchange information in response to their latitudinal “experiences”. Thus, a meta structure can be created that encompasses *experiences* of all its individual structural bodies.

A BODY PLAN

TJELESNI NACRT

Manuel DeLanda states: “Deleuze uses the term ‘abstract diagram’ (or ‘virtual multiplicity’) to refer to entities like the vertebrate body plan, but his concept also includes the ‘body plans’ of non-organic entities like clouds or mountains”.¹⁸ He also explains that body plan does not contain details about the numbers and shape of elements, for instance proportions and shape of limbs of vertebrates, in order to cover a wide spectrum of possible combinations of measurable parameters of their forms.¹⁹ In the context of parametric design, DeLanda says that extensities of a body (which represent longitudes of a body) are represented as a procedure of its designing (procedural programming of its formation, i.e., a body plan, a genotype), and parametric intensities that determine its shape and thus represent the latitudes of a body – a phenotype. Body plan is, therefore, a parametric shell, emptied of its parametric intensities, whereas the body is the totality of latitudes and longitudes that give it shape. When extensities are changing, the structure is polymorphic and when the intensities are changing, the structure is morphodynamic. In computational design techniques, a structural body can be virtually morphodynamic during the design process, but the assessment whether the structure will be morphodynamic after the construction has finished depends on the capacity of the structure for changing its intensities in its lifetime. A body is generated through a procedural instruction. As a genetic means it is also used to form the geometry of soft robots, as a diagram of robotic elements that can be combined into specific sets optimised for certain purposes. Further on, exploring the *space of possibilities*, optimal forms of *complex body plans* of pneumatic structures can be generated, all based on combinations and permutations of established basic body plans.

AIM, METHOD AND MATERIALS

CILJ, METODA I MATERIJALI

This article focuses on the possibilities of constructing pneumatic architectures that could be constructed and at the same time actuated through the use of a modular volume unit elements. In order to make a system

1 This work is based on the research results from the PhD dissertation: *Biomimetic Pneubotics in Architecture: Research Model for Modular Structures* by Davor Andric, completed in 2017 at the University of Zagreb, Faculty of Architecture, under supervision of Karin Serman and Josip Galic, and on subsequent research done by the authors.

2 BIER et al., 2012

3 KRONENBURG, 2003. The pavilion can be packed in a standard container and transported to another location. The main structure consists of eighteen pneumatic beams on “Y” shape pneumatic columns. The active stability system uses tensile pneumatic ties like artificial muscles that counteract the effects of changing outside actions on structure thus allowing for active load distribution management of the structure.

4 LIPSON, 2006

5 SIMS, 1994

6 SIMS, 1994

7 IIDA, LASCHI, 2011

8 DICKINSON, according to: RUS, TOLLEY, 2015

9 This kind of network or *embedded pneumatic network* is sometimes also called *pneunet*.

10 MARCHESE, ÖNAL, RUS, 2014

11 WEVER, 2008

12 ILIEVSKI, MAZZEO, SHEPHERD, CHEN, WHITESIDES, 2011

13 BALLANTYNE, 2007: 8. Ballantyne here quotes Deleuze from his work Spinoza: *Philosophie pratique*, 1970.

14 LIPSON, 2006

15 BALLANTYNE, 2007: 32

16 www.bk.tudelft.nl [10/2009] according to: GRUBER, 2011: 135

17 OOSTERHUIS, 2012: 16

18 DELANDA, 2002

19 DELANDA, 2002

for constructing a plethora of such actively adaptable pnebotic structures, an idea of a *basic body plan* is used to extract basic functional schemas of soft robots, of interactive art and architecture, in order to make a library of elements to generate simple and complex pnebotic structures in architectural design. The goal is to find a set of basic body plans that can be used to construct concrete pnebotic structures of architectural scale by using one single element that could be mass produced but could manifest itself differently according to its local situation within the structure.²⁰

Based on the previously discussed theoretical context, a model for classification of soft robots and soft structures in art and architecture is set up to produce a set of basic body plans for constructing concrete modular soft adaptable structures in architecture. The basic modular element that this research proposes and examines is a soft expanding cube that can generate form and actuate a soft body. The shape of the cube is selected as a basic geometrical unit that enables addition in all three spatial dimensions. A soft cube can also be further folded into other geometrical shapes in order to achieve specific functionality like local rotation or bending etc., within basic body plans.

A basic body plan here is an expression used to describe the structural logic of soft robotic part reduced to its most abstract level. These basic body parts having basic body plans can, further on, form complex bodies with complex body plans. To enable translation of movement from small soft robots to elements of architectural scale, basic body plans are formulated in terms that can best describe construction and transformation properties of a body part.

Examples from the field of contemporary soft robotics and adaptable structures in art and architecture are here sorted according to the manner in which they get modified and transformed through inflation of their pneumatic elements.

RESULTS – FOUR BASIC BODY PLANS

REZULTATI – ČETIRI OSNOVNA TJELESNA NACRTA

Through formal and functional analysis of selected cases of soft robots and soft structures in art and architecture, four main types of basic body plans have been detected. Two of them are then further divided into specific subtypes. The main types are derived from the principal ways in which they produce effect, and subtypes are derived as variants of the same principle used within a type. Basic body plans are corroborated through concrete cas-

es and shown in a summary table (Table I) and in conceptual 3D rendering (Fig. 1).

Basic body plan type A – The first and most simple detected basic body plan is a single element or a group of single elements that are not directly connected to each other. It can be represented by the expression: $BPA = n \cdot UE$. It is important to note that these expressions are not mathematical formulae but short codes instead. In this case it states: (Basic) Body Plan A = n (a number of) Unit Elements.

Art installation *Bubbles* by Foxlin Studio follows this main body plan. It is a pneumatic installation comprised of large pneumatic volumes in space that can deflate or inflate reacting to visitors, by opening or closing the spaces between pneumatic bodies.²¹ Another case enacting this body plan is the *Inflatable bubble stabilizer* by Takuya Onishi.²² It is a system of pneumatic elements that can be inserted into structures damaged in earthquakes to provide temporary stability through inflation. Some similar structural stabilizing bodies are being researched by the Air Dan-shin company in Japan to form an actively responsive system of earthquake building insulation. Pneumatic devices inserted between foundations and the house adaptively inflate according to the type and intensity of the earthquake thus insulating the structure from the ground in an optimal manner.²³ *Bio-Kinesis* by Kim Minwoo and Jo Sunghye, on the other hand, is an interactive soft kinetic media skin or rather art installation consisting of an array of biomimetic pnebots that react to the presence of people.²⁴ Each unit is made of a hard surface onto which a soft body is mounted. Each body works independently of each other and does not influence others' geometry.

Basic body plan type B – The analysis of registered cases has resulted in recognition and definition of the basic body plan B, which describes structures with directly connected pneumatic elements. The research registered three specific subtypes B1, B2 and B3.

Basic body plan type B1 – The first basic body plan of type B is a linear series of connected pneumatic elements. This basic body plan can be written as $BPB1 = x \cdot UE$, since it only has one spatial dimension.

Hartz, Bögle and Schlaich proposed in their paper a pneumatic roof and facade systems that can telescopically shrink and expand depending on the air pressure within the air cushions.²⁵ This can be most succinctly expressed by basic body plan type B1. Further on, *Responsive Structure* is another research project in architectural application of this soft structure mechanism, through which Amin Sadeghi and Mehran Garhlegghi and colleagues

²⁰ Modular pnebotic element represents a series of identical products, which fits into industrial paradigm of mass production, but thanks to different rates of inflating it becomes similar to but different from other elements in use, which altogether fits into post-industrial paradigm of mass production of differences.

²¹ 'Bubbles'

²² ONISHI, 2004

²³ SAKAMOTO, 2008

²⁴ PARK, KIM, 2016

²⁵ HARTZ, BÖGLE, SCHLAICH, 2009

²⁶ 'Studio Integrate: Responsive Structures LDF'

²⁷ SUMOVSKI, 1893

²⁸ COBO ARÉVALO, 2014

²⁹ 'Formeta'

³⁰ 'Pneumatic structure Archives'

³¹ 'Bubbles'; ONISHI, 2004; SAKAMOTO, 2008; 'Bio-kinesis'

³² HARTZ et al., 2009; SUMOVSKI, 1893; 'Studio Integrate: Responsive Structures LDF'

³³ COBO ARÉVALO, 2014; 'Formeta'

³⁴ 'Pneumatic structure Archives'; CHENEY et al., 2013

³⁵ CORRELL et al., 2010; SHEPHERD et al., 2011; SUN, SONG, & PAIK, 2013; SHEPHERD et al., 2013

³⁶ MARCHESE, ÖNAL, et al., 2014; MARCHESE, KATZSCHMANN et al., 2014; ILIEVSKI et al., 2011; MARTINEZ et al., 2013

³⁷ 'Robotics: Soft Hands'; TARCZEWSKI, 2005

³⁸ ALBERT et al., 2013; 'Amorphicrobotworks: Sixteen birds'

from London studio Integrate explore possibilities of designing, manufacturing and construction of light modular adaptable pneumatic structures. By inflating the series of smaller cushions, a pneumatic actuating element contracts, causing the connected main element (a series of bigger cushions) to bend, thus achieving lifting to allow for ventilation of space and penetration of light.²⁶ Another, older example of this type is a series of tubular elements connected linearly in order to make a self-erecting *bridge over a precipice* proposed in 1893 by J. A. Sumovski. A series of tubes is inflated, at the start all but the first one; and after inflating the first one the structure is then lifted.²⁷

Basic body plan type B2 – These are all soft bodies sharing a basic body plan: $BPB_2 = xy \cdot UE$. This means that the unit elements are connected to each other and arranged into planar structures.


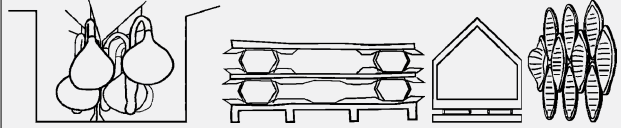

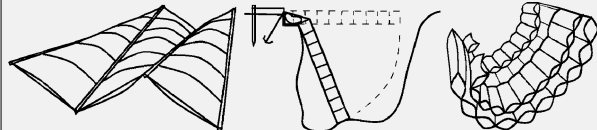
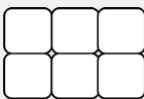
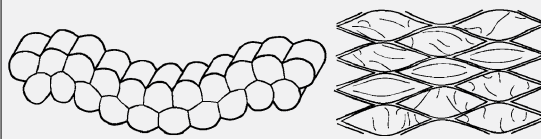
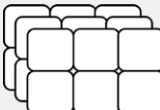
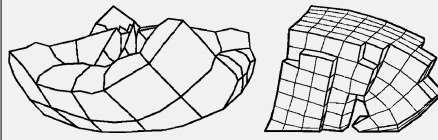


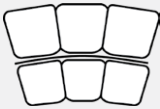
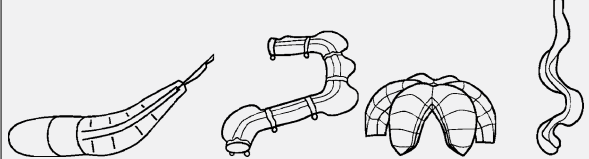

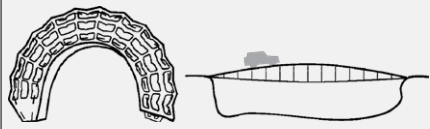


Prototype of a varying morphology beam from 1970 by José Miguel de Prada Poole²⁸ is just such a structure made of a series of interconnected pneumatic cushions staged into two rows. The beam changes its curvature depending on the intensities of pressure in individual cushions, and the offset of rows by half the cushion makes the change in curvature even more intense. *Pneumatic Envelope* by Rick Sole²⁹, further on, is a surface structure made of pneumatic cushions with a layer of light blocking material. Inflating individual cells results in setting the light-blocking lamina apart so that the light can pass through the structure. The envelope thus becomes an adaptive skin regulating insulation in relationship to interior needs and outside conditions. Inflation of one cushion pulls the surrounding cushions to itself, since inflation reduces the size of the cushions in the system plane, but that influence is not severe and does not compromise the functioning of the system.

Basic body plan type B3 – This basic body plan is a three-dimensional version of the same basic body plan, so the expression for it is: $BPB_3 = xyz \cdot UE$.

According to this principle functions the pneumatic installation *Dynamat* by Mark Fisher and Simon Conolly from 1971. It is a structure made of an array of interconnected square pneumatic cushions arranged in tree layers, which changes shape depending on which cushions are inflated or deflated. Its movements were pre-programmed by means of a sound recording that dictated inflation and deflation of parts of structure producing different concave or convex forms of its double layered surface.³⁰ On the other hand, *Evolving soft robots with multiple materials* by Cheney, MacCrudy, Clune and Lipson are

TABLE I BASIC BODY PLANS WITH LIST OF CASES

TABL. I. OSNOVNI TJELESNI NACRTI S PRIMJERIMA

Type, expression and graphical scheme	Cases: sketches and names
<p>A (unit element) $BPA = n \cdot UE$</p> 	 <p><i>Bubbles; Inflatable bubble stabilizer; Air-floating-type base isolation device; Bio-Kinesis</i>³¹</p>
<p>B1 (linear series) $BPB_1 = x \cdot UE$</p> 	 <p><i>Pneumatic structures in motion; Bridge over a precipice; Responsive structure</i>³²</p>
<p>B2 (planar series) $BPB_2 = xy \cdot UE$</p> 	 <p><i>Prototype of a varying morphology beam; Pneumatic Envelope</i>³³</p>
<p>B3 (spatial series) $BPB_3 = xyz \cdot UE$</p> 	 <p><i>Dynamat; Evolving soft robots with multiple materials</i>³⁴</p>
<p>C1 (flexible side + expandable side) $BPC_1 = FS + ES$</p> 	 <p><i>Chain structure soft robot; Multigait soft robot; Multi-chamber bending actuator prototype; Self healing soft robots resilient to puncture</i>³⁵</p>
<p>C2 (flexible middle + expandable sides) $BPC_2 = FM + n \cdot ES$</p> 	 <p><i>Autonomous soft robotic fish; 2D robotic manipulator; Soft robotic compliant grippers; Robotic tentacles with three-dimensional mobility</i>³⁶</p>
<p>C3 (membrane + expandable core) $BPC_3 = EM + FS$</p> 	 <p><i>Soft Fingers; Deployable inflated bridge</i>³⁷</p>
<p>D (hard parts + expandable part) $BPD = HP + EP$</p> 	 <p><i>Soft robotic arm; Sixteen birds</i>³⁸</p>

virtual soft robots made of several different types of materials in three-dimensional shapes. Individual *voxels*³⁹ can contract, expand or else be inert soft or inert rigid. By various placement of voxels and their actuation, a plethora of soft robots with different locomotion can be generated.⁴⁰

Basic body plan type C – The following main basic body plan is that of type C, as a combination of flexible and expandable parts, which can be developed in three basic subtypes: C₁, C₂ and C₃.

Basic body plan type C₁ – This basic body plan is perhaps the most important because it enables the construction of linear and planar soft bodies that bend. They achieve this quality through their construction that consists of sides that bend and sides that expand. The structure can be of same material with different thicknesses or a composite of two or more materials. Basic expression describing these bodies is: $BPC_1 = FS + ES$.⁴¹ Soft robots with this type of basic body plan are often made of a series of modular elements that use bending, like for instance a *chain structure* soft robot made of 6 bending segments to achieve locomotion (crawling in this specific case).⁴² Hence these robots' body can be written as $CBP = 6 \cdot BPC_1$, CBP meaning *complex body plan*.⁴³ Other robots can have still more complex design like a *multigait soft robot* with a central body and 4 segments connected to it like four limbs, and which is then capable of crawling and undulating with complex and sophisticated movements.⁴⁴ These robots' complex body plan consists of one middle segment and 4 limbs attached to it, i.e., $CBP = BPC_1 + 4 \cdot BPC_1$.⁴⁵ Other examples of soft robots with this type of bending elements are a *multi-chamber bending actuator prototype*⁴⁶ and *self-healing soft robots resilient to puncture*.⁴⁷

Basic body plan type C₂ – This basic body plan has a flexible middle with expandable sides. It hence has the ability of producing bending to either side of the body. If the sides are arranged in different directions, a more intricate spatial bending can be achieved. The expression is $BPC_2 = FM + n \cdot ES$.⁴⁸ Most of the soft robotic examples have two, some three sides that expand, but it is possible to have more.

Autonomous soft robotic fish, for instance, has a tail made of a double-sided expandable segment that can bend in two directions and propel the robot in the water.⁴⁹ Its complete body plan is then $CBP = \text{hard front part} + BPC_2$. Another case is *2D robotic manipulator*, which is a soft robot that consists of a series of modules that make a soft pneumatic arm. The middle is flexible, and it holds tubes that supply air to expandable sides in each module. Through variable bending of indi-

vidual modules, a complex planar locomotion is achieved enabling the arm to move through tight spaces.⁵⁰ Its concrete body plan is thus $CBP = 6 \cdot BPC_2$. Further on, soft robotic *compliant grippers* made in the shape of a starfish can bend its segments out of plane changing its curvature from concave to convex depending on which side of the gripper expands thus enabling the robot to grab and release objects.⁵¹

Some examples of this body plan include more intriguing construction layout of embedded materials to achieve even more complex locomotion. *Robotic tentacles with three-dimensional mobility*, for instance, can produce complex motions in one specially designed variation of this body plan. Strategically placing flexible sides in relation to expandable sides, tentacles can achieve complex three-dimensional motions, thus gripping and manipulating objects of complex shapes.⁵²

Basic body plan type C₃ – This basic body plan is a sort of an inverse basic body plan C₂, meaning it has expandable middle with flexible sides. Hence the expression for this basic body plan is $BPC_3 = EM + FS$. Sides can be different in their properties: one can be more flexible than the other, only in tension or more rigid etc.

For instance, *Printable Fingers* are soft robotic structures with 3D printed outer cage that has one flexible and one accordion-like expandable side and inner soft balloon-like tube. Expansion of the tube causes the stretching of accordion-like side which causes the finger to bend.⁵³ *Tensairity* structures, further on, although not designed as robotic, have the same basic body plan: upper more rigid compression side, inner pneumatic cushion, and lower tension side. The case of *Deployable inflatable bridge concept* by Tarczewski represents a structure composed of cushions of various thickness between an upper compression and lower tension layers.⁵⁴

Basic body plan type D – Basic body plan type D is a basic body plan that consists of a pneumatic actuator mounted on elements of stable form (quasi hard parts) in a way that produces rotation or bending. Expression for this basic body plan can be: $BPD = HP + EP$.⁵⁵ Soft actuator can operate by expansion or by contraction (which is actually an effect of expansion in other dimensions).

Soft robotic arms like some of those created at Otherlab are made of pneumatic parts of constant pressure and form, and pressure actuator chambers that move those parts.⁵⁶ Pneumatic art installation *Sixteen Birds*, on the other hand, is made of interactive "birds" that are each made of long inflated conical wings and a cushion in the middle. Birds wave their wings when cushion expands and changes the angle between two wings.⁵⁷

39 This compound word is constructed from words volume and pixel.

40 CHENEY, MACCURDY, CLUNE, LIPSON, 2013

41 Body plan C₁ = flexible side + expandable side

42 CORRELL, ÖNAL, LIANG, SCHOENFELD, RUS, 2010

43 Complex body plan = (series of) 6 (segments of) body plan C₁

44 SHEPHERD et al., 2011

45 Complex body plan = body plan C₁ (torso) + 4 (segments of) · body plan C₁ (limbs)

46 SUN, SONG, PAIK, 2013

47 SHEPHERD, STOKES, NUNES, WHITESIDES, 2013

48 Body plan C₂ = flexible middle + multiple expandable sides

49 MARCHESE, ÖNAL, RUS, 2014

50 MARCHESE, KATZSCHMANN, RUS, 2014

51 ILIEVSKI, MAZZEO, SHEPHERD, CHEN, WHITESIDES, 2011

52 MARTINEZ et al., 2013

53 'Robotics: Soft Hands'

54 TARCZEWSKI, 2005

55 Body plan D = hard part(s) + expandable part

56 ALBERT, LYNN, GRIFFITH, 2013

57 'Amorphicrobotworks: Sixteen birds'

58 The number of cases shown in this paper does not reflect the actual frequency of detected body plans but rather their most interesting and plastic manifestations.

DISCUSSION AND CONCLUSION

DISKUSIJA I ZAKLJUČAK

The model presented here, based on the idea of a basic body plan, is one possible way to analyse the phenomenon of soft movement in nature in its capacity for application in the design of pneubotic structures in architecture. It represents a level of abstraction needed to transcode the structure of soft bodies from nature into another field of application. In this regard, since a certain level of abstraction was already needed to transcode the logic from nature into the field of soft robotics (and in some cases into art and architecture), this same abstraction is in some way encoded in their body plans. A body plan that encodes the functional diagram of a natural model should encapsulate the transformation capacity of the natural model into targeted structure. In this way this model is biomimetic.

Body plans that were detected in this analysis should not be considered the only ones, but rather the most obvious and appropriate to be reconstructed using volumetric modular elements. In case of linear actuation elements, like soft muscles for example, a set of different body plans might need to be established.

Examples for some body plans registered here are much more frequent than others.⁵⁸ This might be regarded as an indicator of possible distribution of basic body plans among pneubotic structures that could be used in architecture. For instance, the most frequent cases that could be found in soft robotics are among robots of body plans type C and D, since their primary transformation effect is achieved through bending, while body plans type A and B have fewer examples because they need more expansion elements to produce similar results. Of course, this should not be taken as a rule, since architectural structures have problems of different nature from those of soft robots and maybe a body plan that is less “successful” in the field of soft robotics might be quite efficacious in the aspect of architectural application.

Applied to the design of architectural structures, body plans detected here, containing only the information about the type of parts and how they are connected but not their parametric values, can generate multiple structural forms. Therefore, they are virtually

polymorph, and the specific instances of their multiplicities represent their actualities that can change according to the inflation of specific parts they are generated from. The inflatability of their pneubotic elements gives them the ability of actualizing their different virtualities in real time through dynamic changes of their form; they are not only virtually but also actually morphodynamic.

Combining multiple basic body plans should produce complex pneubotic structural bodies that inherit their characteristics from basic body plans they consist of. – It is the addition of parts that causes the multiplication of effects allowing for the emergence of new properties and behaviours. The question how a body plan can contain transformation capacities of a body and how they can manifest within a complex body is an intricate topic for further research that could be carried out using this model.

This model is expected to find application in more fields of research: 1) in the field of architectural theory this model opens prospects for rethinking the ideas of bionic and parametric design, idea of a structural body, body plan, polymorphism, embedding, encapsulation, inheritance, virtuality, soft and interactive architectures etc.; 2) in the field of architectural structures this model could be applied in the design of lightweight, mobile, temporary structures that can actively adapt or react to changes thus protecting users or augmenting some aspects of their environment; 3) in the field of bionic design, apart from the detection of body plans and translating natural structures into architectural field, the model could be used for the development of parametric morphogenetic tools for designing soft adaptive structures; 4) in the field of robotics this model is suitable for research of sensors, control procedures of soft pneubotic morphologies, as well as research of emergent patterns of behaviour in swarm robotics and artificial intelligence. And finally, the represented model also opens up the field for development of other forms of modular pneubotic elements and group of elements for achieving other levels of complexity and efficiency of soft bodies in architecture, as well as the development of metrics for human-robotic interaction and digitally driven architectures.

[Written in English by the authors]

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SUMMARY

SAŽETAK

OSNOVNI TJELESNI NACRTI ZA MEKANE MODULARNE PNEUBOTSKE KONSTRUKCIJE U ARHITEKTURI

Biomimetičke pneubotske konstrukcije u arhitekturi recentna su pojava u ranoj etapi razvoja koja prati razvoj mekih robota. Meki roboti, zahvaljujući konstrukciji od rastezljivih materijala, često oponašaju konstrukciju i pokrete živih bića. Većina suvremenih pneubotskih konstrukcija u arhitekturi koristi linearne pokretačke elemente poput mekih misica ili tvrdih klipova, a njihova se morfodinamičnost kreće od jasnih i brzih pokreta te promjena oblika poput onih konstrukcije *Tower 2* grupe *Hyperbody*, do manje izraženih poput onih pneumatski prilagodljivog paviljona *Airecture* tvrtke Festo. Pneubotske konstrukcije često ostavljaju dojam kao da su živa meka tijela. Pojam 'tijela' u mekoj robotici već je uvriježen i često se koriste pojmovi poput *tijelo* i *mozak* da bi se opisala konstrukcija robota i softver za njihovo upravljanje, kao i neki zoomorfni i antropomorfni nazivi poput *ud*, *noga*, *trup* i dr. Također, koriste se pojmovi posuđeni iz biologije, kao što su *genotip* i *fenotip* za postupak nastanka nekog oblika, odnosno njegove specifične izvedenice. Opisujući klasična robotska tijela, neki autori dodatno naglašavaju razliku u odnosu na meke robote koristeći pojmove poput 'tvrdi roboti' ili 'roboti tvrdog tjelesnog nacrti'.

Pojam tjelesnog nacrti, nadovezujući se na pojam tijela kako su ga uspostavili Gilles Deleuze i Felix Guattari, arhitektonskoj je struci približio Manuel Delanda obrađujući upotrebu genetičkih algoritama u arhitektonskom projektiranju. Dok prva dva autora opisuju pojam tijela kroz pojmove dužine i širine, gdje su dužine set odnosa između elemenata, a širine set utjecaja na tijelo, tj. intenzitetska stanja sila – Delanda daje tjelesni nacrt kao proceduru ili računalni napatuk kojim se generira neka geometrija, naglašavajući kako tjelesni nacrt ne sadrži vrijednosti parametarskih odrednica nekog tijela. Time tjelesni nacrt ostaje dovoljno otvoren da iz njega može nastati mnogo različitih pojedinačnih

tijela. Pojam tijela neki autori, npr. istraživačka grupa *Hyperbody*, proširuju dalje na pojam 'hiper-tijela' – tijela prožeta informacijama i sposobna za interakciju s okolinom i drugim tijelima zgrada. Promatrajući tjelesni nacrt kao proceduralni dijagram nastanka brojnih tijela, tijela mekih robota, umjetničkih instalacija i prilagodljivih konstrukcija u arhitekturi mogla bi se rastaviti na osnovne sastavne dijelove. Time se dobiva set osnovnih tjelesnih nacrti koji se mogu koristiti za istraživanje optimalnih kombinacija elemenata za generiranje kompleksnih pneubotskih konstrukcijskih tijela u arhitekturi. U ovome istraživanju razmatrana je mogućnost konstruiranja pneubotskih konstrukcija u arhitekturi koristeći jedinstveni volumenski element kao gradbeno-pokretačke jedinice. Ideja osnovnoga tjelesnog nacrti korištena je kao sredstvo funkcionalne analize konstrukcije i pokreta mekih tijela da bi se dobio set osnovnih tjelesnih nacrti iz kojih je moguće konstruirati konkretne pneubotske konstrukcije arhitektonskog mjerila koristeći jedinичni serijski element. Model koristi osnovni jedinичni volumen – kocku kao meki element koji se spajanjem bridova može preobiti u druge oblike poput prizme ili jastučica. Osnovni tjelesni nacrt sveden je na apstraktni izraz koji najbolje opisuje konstrukciju i transformacijsko svojstvo elementa.

Analizirani primjeri razvrstani su u četiri glavna tipa tjelesnih nacrti, s time da su dva tipa dalje podijeljena u podtipove. Uspostavljeni tipovi tabelarno su prikazani s pripadajućim shemama i primjerima, a simulacija mogućega fizičkog izgleda dana je kroz konceptualni 3D prikaz.

Tako dobiveni osnovni tjelesni nacrti jesu: 1) tjelesni nacrt tipa A – pojedinačni ili grupa posredno povezanih jedinичnih elemenata; 2) tjelesni nacrt tipa B – nizovi međusobno direktno spojenih elemenata; B1 kao linijski niz, B2 kao plosni i B3 kao prostorni niz; 3) tjelesni nacrt tipa C kao kombinacija rastezljivi

vih i savitljivih dijelova, i to: C1 tip s jednom savitljivom i jednom rastezljivom stranom, C2 tip sa savitljivom sredinom i rastezljivim stranama, C3 tip s rastezljivom sredinom između savitljivih strana, te 4) tjelesni nacrt tipa D kao meki pokretački element između elemenata konstantnog oblika.

U članku razvijeni model zasnovan na ideji osnovnih tjelesnih nacrti predstavlja apstrakciju logike mekih pokreta u prirodi (koji je jednim dijelom već ugrađen u konstrukciju analiziranih primjera) za prenošenje u polje mekih konstrukcija pa se može koristiti i za daljnja istraživanja biomimetike u arhitekturi. Jedno od važnih pitanja koje se time postavlja i može se dalje istraživati koristeći ovaj model jest: kako osnovni tjelesni nacrt može prenositi transformacijske mogućnosti mekog tijela i kako se one manifestiraju u tijelu složenom od nekoliko osnovnih tjelesnih nacrti?

Očekivana primjena ovoga modela pokriva više polja i relevantna je, između ostalog: 1) u polju arhitektonske teorije – u pogledu razmatranja o idejama bioničkog i parametarskog projektiranja, konstrukcijskih tijela, tjelesnog nacrti, ugrađivanja i nasljeđivanja svojstava, virtualnosti i aktualizaciji, mekoj i interaktivnoj arhitekturi i dr.; 2) u polju arhitektonskih konstrukcija – projektiranje laganih, prijenosnih, privremenih, prilagodljivih i aktivno reagirajućih konstrukcija; 3) u polju bioničkog oblikovanja – razvoju parametarskih morfogenetičkih postupaka za projektiranje prilagodljivih konstrukcija; 4) u polju robotike – razvoju osjetljivih i pokretačkih postupaka mekih konstrukcija, kao i istraživanju uzoraka ponašanja robota, robotskih rojeva i umjetne inteligencije; 5) drugim mogućnostima razvoja modularnih pneubotskih elemenata i sklopova složenih i učinkovitih konstrukcijskih tijela, kao i metrika ljudsko-robotske interakcije i razvoja drugih oblika digitalno pogonjenih konstrukcija u arhitekturi.

BIOGRAPHIES

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