Indeterminate Architecture*: Scissor Pair Transformable Structures*

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Introduction

Most traditional architectural theories and practices aim at designing unique, fixed and ideal solutions. The general belief is that the final shape of a building can be achieved by analyzing present situations, such as clients' stated needs, demands and desires. Likewise, this approach is based on descriptions and assumptions, which consider future situations as certain, invariable and in a particular moment in time. However, are the situations of the present representative of a reality to be produced in the future, during the life of the building? And, moreover, are these situations fixed and invariable throughout time?

The vision here is that during the design process, future situations are uncertain, since not only buildings generate unprecedented and unexpected situations, but also these situations evolve and change through use and time. This paper addresses this problem through proposing an indeterminate architecture, wherein the building remains in an open-ended process of definition and redefinition according to clients' incidental needs, demands and desires. This vision is defined by two complementary design considerations: *Designing the Range* and *Enabling the Choice*. While *designing the range* refers to transformable buildings able to offer a variety of states, *enabling the choice* refers to the users' selection of states, within the range and according to emergent situations [1].

This paper is aligned with some seminal ideas proposed in the sixties and seventies, which promote the design of a range to enable the choice through an indeterminate architecture sympathetic to uncertainty, incompleteness and emergent situations. More specifically, this paper attempts to materialize the intriguing and utopian architecture envisioned by the Archigram movement in the sixties [2], and, likewise, aims at radicalizing the inventive and technical kinetic architecture proposed by William Zuk and Roger H. Clark in the seventies [3].

It is important to clarify that, even though it is possible to associate this research with contemporary explorations of adaptable, interactive and performative architectures [4], the strategy here is to refresh the current discourse and contribute by merging old ideas with theories and technologies of today. The objective is to materialize and radicalize the seminal ideas about indeterminate architecture by relating the engineering knowledge on scissor-pair transformable structures with the Artificial Intelligence (AI) theories and techniques on robotic control within uncertain environments. While scissor-pair transformable structures materialize indeterminacy through mechanical and physical shape variation, robotic control radicalizes indeterminacy by enabling the modification of the structure's behaviour in real-time.

The structure of this paper is organized around two sections, the two directions for the design of indeterminate buildings: *Designing the Range* and *Enabling the Choice*. Both sections present, first, an architectural background to give initial definitions and directions, second, a technical approach to extend the scope of current indeterminate solutions, and, third, an empirical experiment to propose some novel architectural applications. The first section, *Designing the Range*, addresses the uncertainties about the future use of the building through the design of a range of alternatives instead of a unique, fixed and ideal solution. While Archigram's ideas are presented to show how indeterminacy can be pushed to an extreme by proposing flexible and almost immaterial building environments, kinetic architecture is used to address the technical domain of indeterminacy by mechanical structures able to transform according to variable demands. This theoretical background is then related to the analysis of scissor-pair transformable structures, wherein existing engineering solutions are studied in order to find novel shapes and behaviours. Finally, a novel type of scissor-pair solution, able to transform in a non-uniform manner [5], is proposed along with a digital and physical prototype to show some architectural applications.

The second section, *Enabling the Choice*, focuses on how the range of alternatives extends the design process to the real-world through the continuous shape definition and redefinition according to users' demands. While Archigram illustrates how buildings could be designed as machines that interface between the environment and the user, kinetic architecture shows the advantages and limitations of actuated mechanisms. Artificial Intelligence (AI) theories and techniques are then presented to show how to design indeterminate solutions: by engineering machines that interface directly with the real-world, self sense, record and learn from their own physical performance. These AI techniques are, finally, incorporated into the novel scissor-pair solution using sensory-motor actuation, to radicalize indeterminacy by facilitating the modification of the building-machine's behaviour in real-time.

A final section provides a reflection about the work's weaknesses and strengths, and some future lines of research within the design of indeterminate buildings and scissor-pair transformable structures.

01_Designing the Range

Range of Alternatives

Assuming the uncertainties about the future use of a building implies a different notion of the design process. Instead of the architect's attempt to find a unique, fixed and ideal solution, the challenge is designing an indeterminate solution, offering a *range of alternatives* for the users of a building. In order to design an indeterminate architecture, the designer has to envision a range of possibilities, leaving part of the definition open, according to incidental situations that may occur in time and throughout the use of the building.

Archigram acknowledges that building should express "its habitants' supposed desire for continuous change" [6]. Therefore, they envision an indeterminate architecture in an open-ended process of shape definition, wherein the architect has to design the system or technical apparatus

that would enable the choice of a solution out of a number of alternatives [7]. According to this view, the design process is reoriented towards the definition of flexible systems: buildings able to transform themselves to offer a *range of alternatives* instead of unique fixed and inflexible solutions. For Archigram, indeterminacy is materialized in that way, by designing almost immaterial, formless and purposeless building environments.

One of Archigram's most radical projects in relation to indeterminacy corresponds to *The Thing*, designed by David Greene and Michael Webb in the context of the *Living City* installation in London 1963. Instead of designing a traditional building Greene and Webb proposed a placeless triangulated structure floating "with an unstated purpose, hopefully benign, arriving in a bleak landscape" [8]. Here, the shape and physical boundaries of the building are dissolved, pushing indeterminacy to an extreme, wherein the range of alternatives is so broad and open that the building almost disappears. Moreover, *The Thing* not only responds passively to uncertain situations but rather its radical indeterminacy is an active agent that creates and fosters an even more ambiguous and emergent reality.

Following the utopian lines of the Archigram movement, Zuk and Clark propose a more technical approach to indeterminacy by introducing the concept of *kinetic architecture*. They show how the Archigram's approach to indeterminacy could be materialized through transformable buildings, able to change their shape in order to meet different functions. According to them, the impossibility of foreseeing future changes would lead to the incompleteness of the design process and its extension into the realm of physical kinetic buildings. They argue that, since the design process is incomplete and the form can be kinetically changed, the initial built form does not have to be correct and that, instead, the designer may offer a range of possible states: "The architect/designer will provide a range of forms capable of meeting a range of pressure changes" [9].

This range of alternatives, in the case of kinetic architecture, corresponds to the transformation and multiple states that a system is able to produce according to the movement and rearrangement of its internal components. However, according to Zuk and Clark this approach to indeterminacy implies the prediction of the range of possible changes that may occur in the future. Likewise, the form can only "respond to a range of functional changes possible within the initial envelop limitations" [10]. Even though kinetic architecture offers a more technical and possible approach to indeterminacy, it also restricts the freedom and reduces the radicalism of the utopian and playful ideas proposed by Archigram. The kinetic idea offers a limited approach to indeterminacy. It is necessary to know the range of possible situations beforehand, to design systems that have predetermined possible states. Therefore, the challenge, at this stage, is to design a range as broad, open and flexible as possible, studying the in-between states and analyzing the different shapes that are produced. It is about probability, the more variety of the system, the more the chances to meet the change of pressures.

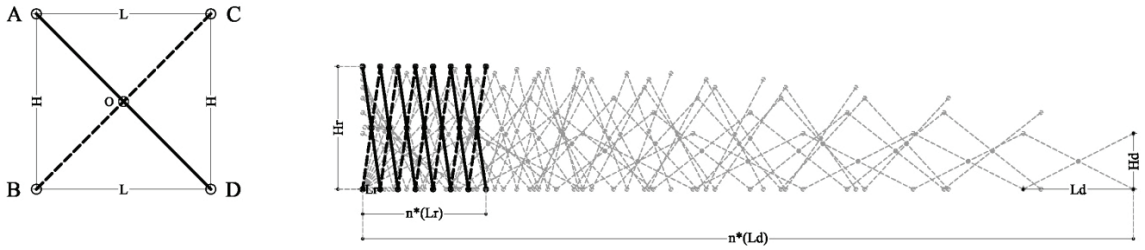
Scissor-pair Transformable Structures

Kinematics is the field that studies the geometry and motion of mechanical systems [11]. In a mechanism, the different components move relative to each other according to the geometry and the degrees of freedom of the system. *Scissor-pair transformable structures* are mechanisms that

have one degree of freedom, which enables the internal propagation of movement, from one component to another. These mechanisms are able to transform as they follow a sequence of states, changing physically from one overall shape to another in a continuous process, offering us the chance to design and build indeterminate physical solutions. Even though their transformation capabilities have been used in engineering design to create and optimize collapsible structures, they have great potential if considering the in-between states, the range of possible shapes, between retracted and deployed positions.

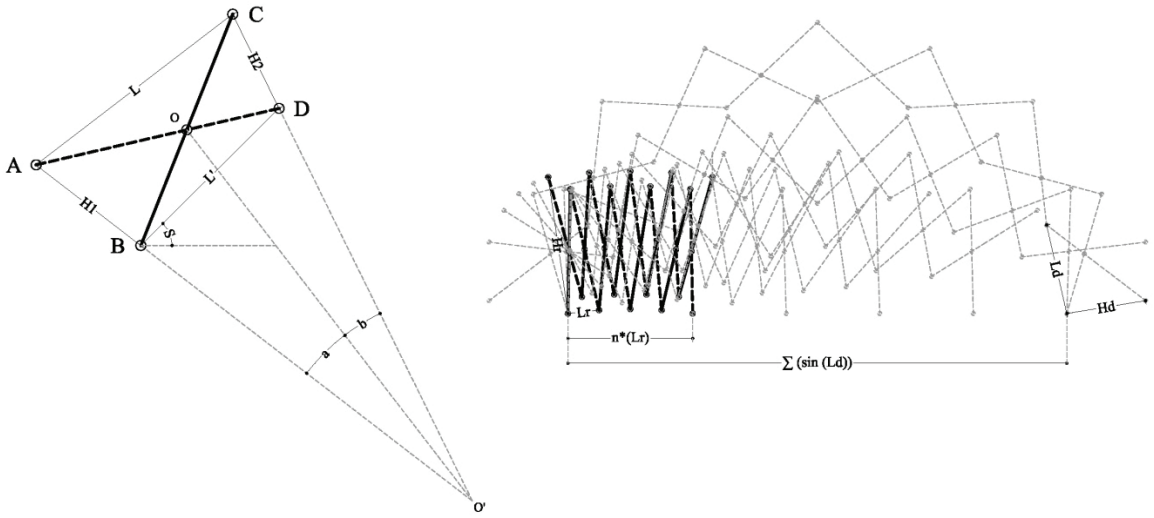
A simple scissor-pair transformable structure can be made from a pair of straight and rigid bars connected in the middle with a pivot or *scissor* hinge. This initial component is called *scissor-pair* and it defines a single-degree-of-freedom mechanism [12]. Through the assembly of these scissor-pair components it is possible to create two- and three-dimensional scissor-pair transformable structures. The single-degree-of-freedom property enables the control of the transformation process through the propagation of rotations from one scissor-pair to the next one and vice versa. In other words, because all scissor-pair components are linked, the rotation of one local assembly will affect the behaviour of the entire structure. This principle of propagation is essential because it reduces the actuation and control mechanism to one variable, the rotation of only one component. It also determines the synchronized and smooth transformation between states [13].

These types of structures have been generally used for rapidly assembled constructive systems which are able to transform their shape between two extreme states: from a compact and retracted state to an extended and fully deployed one. Some applications have been proposed in movable theatre structures [14], expandable space structures [15], collapsible portable shelters [16], deployable domes [17], and retractable roof structures [18]. In all these applications the main objective has been to optimize the ratio of extended and contracted length and to find advantageous structural configurations.



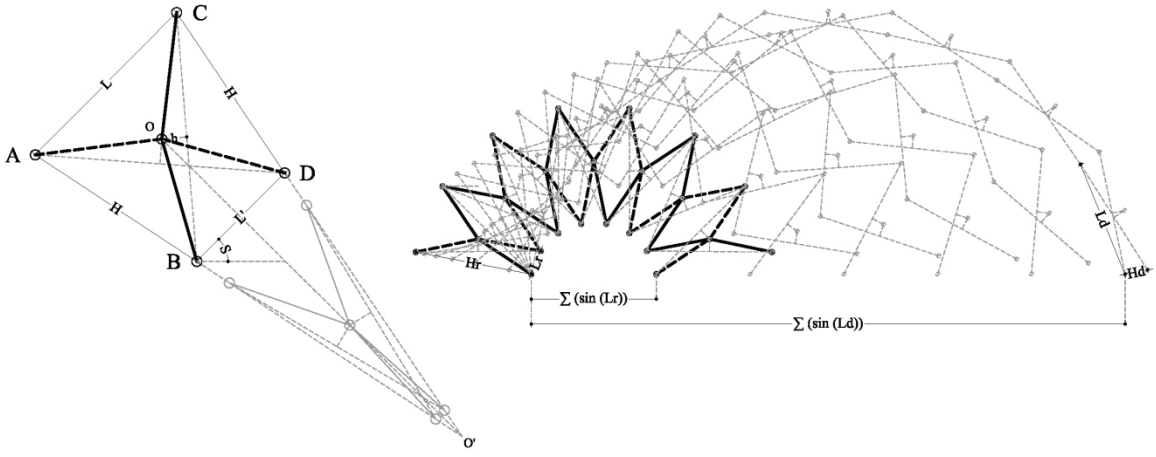
[fig.1] Centre scissor-pair solution

The structural engineering literature covers a reasonable understanding of the shapes and behaviours that can be designed and built using the single-degree-of-freedom property as a constraint. There are mainly three general approaches to the problem according to the shape of the rigid bars and the position of the scissor hinge: the *centre scissor-pair*, the basic and traditional configuration used by Edwards and Luckey [19], the *off-centre scissor-pair*, pioneered by Pinero, Zeigler and Escrig [20], and the *angulated scissor-pair*, discovered by Hoberman and further developed by You and Pellegrino [21].



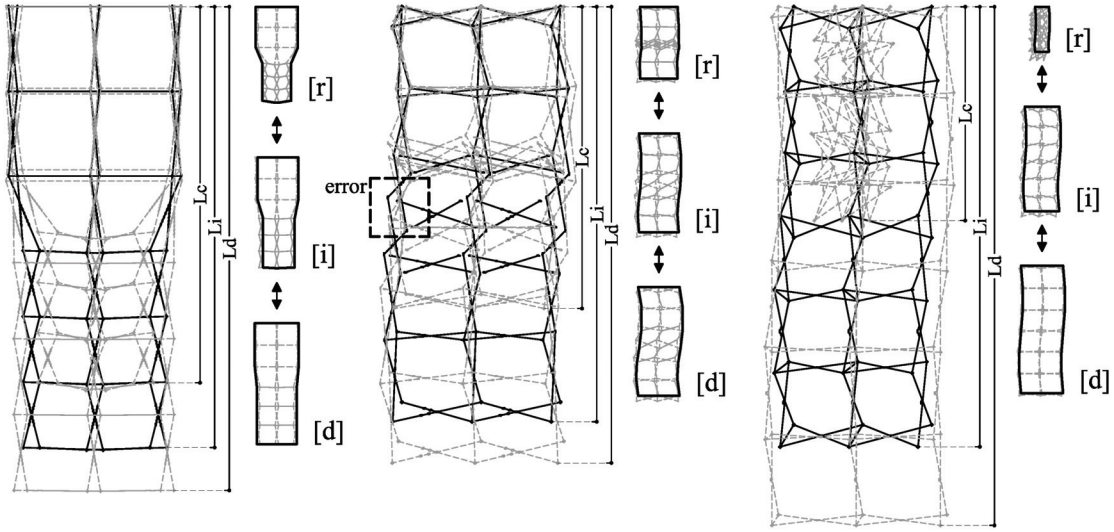
[fig. 2] Off-centre scissor-pair solution

Figures 1, 2 and 3 show the different types of scissor-pair transformable structures and the shapes and behaviours they produce in the in-between states, between retracted and deployed states [22]. However, the intention, here, is neither the optimization of collapsibility nor the structural performance of the systems, but rather the flexibility of the range, the variety of shapes the systems are able to produce. By analyzing the different shapes within the range of the transformations, it is possible to note that the *off-centre* solution is the only one that behaves in a non-uniform manner, generating a continuous transformation from planar to curved profile while deploying [fig. 2]. The centre and the angulated solutions behave uniformly and, thus, the overall shape during transformation remains constant. Particularly, the angulated solution offers great advantage since it enables the creation of transformable curved profiles. In-between configurations, however, are only scaled versions of each other and, therefore, the transformation of these types of solutions does not offer a variety of shapes.



[fig. 3] Angulated scissor-pair solution

As shown in figure 4, while the uniform behaviour of the centre and angulated solutions enable three-dimensional assembly, the off-centre solution generates an *error*. The unique off-centre property of non-uniform behaviour during transformation—wherein the in-between states correspond to different shapes—disallows the possibility of three-dimensional assembly. This can be explained by analyzing how the two lines A-B and C-D, and their projection towards the intersecting point O', change their angle during transformation. Within centre and angulated structures the transformation follows these control lines, which are fixed, whereas in the off-centre solution they change throughout transformation, disallowing three-dimensional assembly.



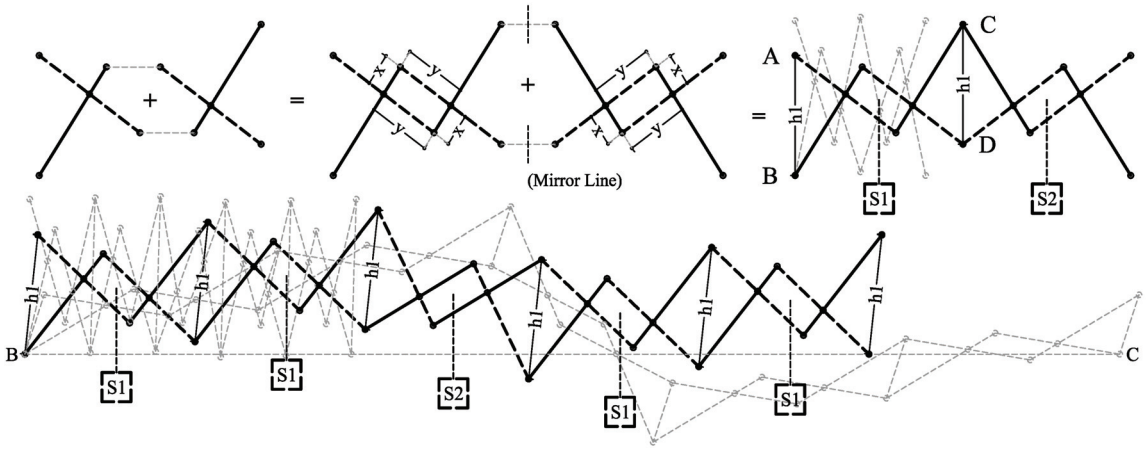
[fig. 4] From left to right: Three-dimensional assembly of centre, off-centre and angulated solutions

Even though centre, off-centre and angulated solutions have provided a valuable contribution to the design of transformable structures, the repertoire of possible applications is still limited to a small number of shapes and behaviours. These transformable structures have been designed through an engineering and analytical approach that aims at optimizing collapsibility and structural performance without considering the in-between states as an opportunity to generate a range of variable shapes. Nevertheless, these solutions correspond to a starting point for the development of a novel solution, able to combine their properties and advantages: on the one hand, the three-dimensional capabilities of the centre and angulated solutions, and, on the other hand, the non-uniform transformation of the off-centre solution, controlled by single actuation: a transformable structure able to offer a range of variable shapes, a range of alternatives, aiming at the construction of physical indeterminate solutions.

Experiment 01: Non-uniform Transformations

It is possible to combine two off-centre scissor-pair components in a novel manner to create a new type of solution: the *double scissor-pair* [23]. This component enables three-dimensional assembly without losing the important property of non-uniform behaviour. The discovery of this novel scissor-pair component is the result of an experimental study in which existing solutions are methodically modified and analyzed in search of emergent properties and

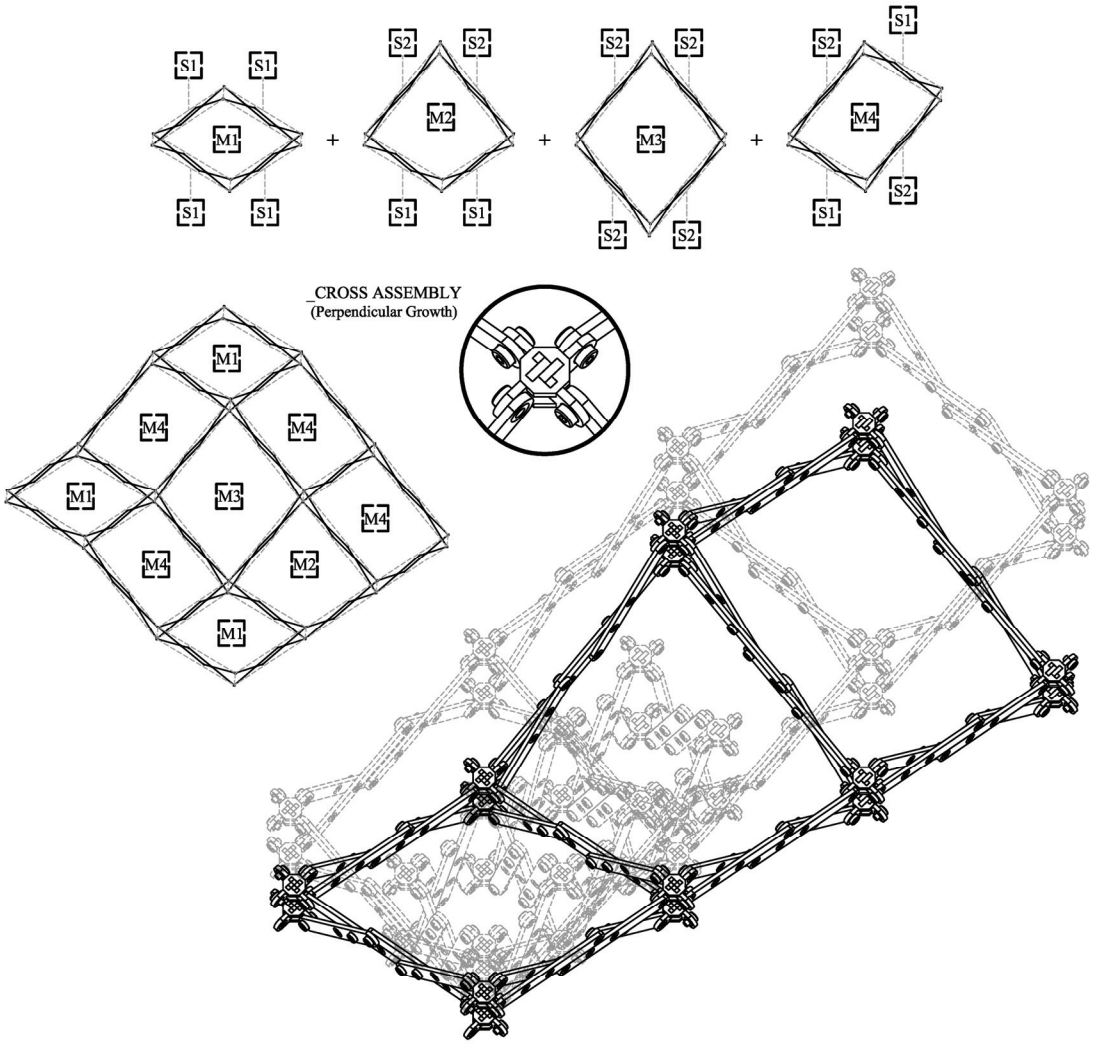
behaviours [24]. As shown in figure 5, the double scissor-pair component corresponds, simply, to the use of two off-centre components, but according to a specific proportion—determined by x and y—between their scissor hinge positions. By changing the relation between x and y, it is possible to define several types of components and therefore different shapes and transformations. According to a specific x and y relation, two compatible components can be created: S1 and S2, which are mirrored version of each other. These two versions can be combined in arrays to create two and three-dimensional configurations. The most important feature of this novel component is that, while keeping the off-centre quality of non-uniform behaviour, the lines A-B and C-D keep parallel to each other during transformation and, therefore, three-dimensional assembly is possible.



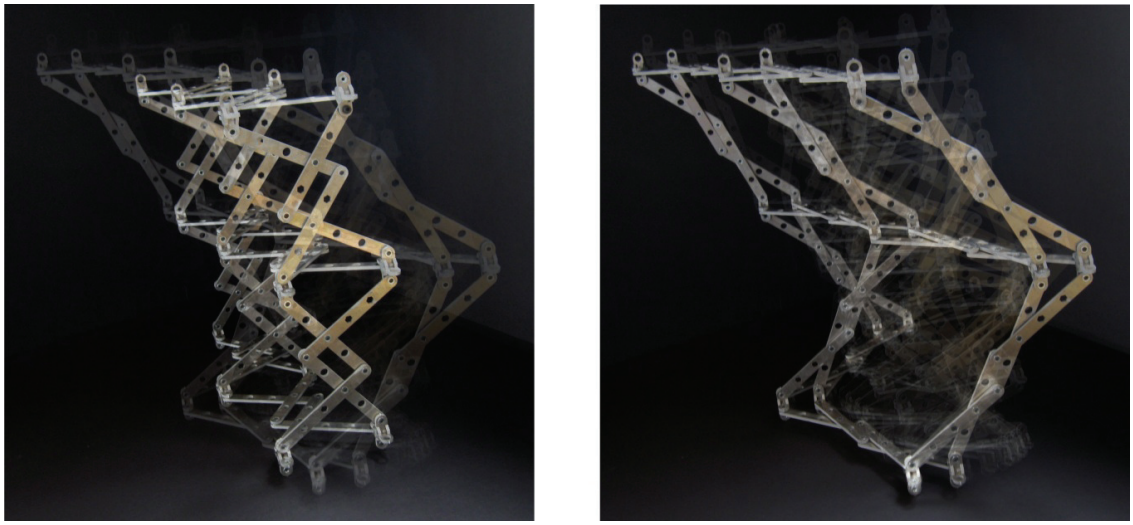
[fig. 5] Double scissor-pair component: proportions and two-dimensional array

Figure 6 explains how three-dimensional assembly is possible. S1 and S2 can be combined in four different ways creating four modules—M1, M2, M3 and M4—that can be also combined to create larger configurations. The three-dimensional connection is possible by using a *cross assembly* that enables linear and perpendicular assemblies among components.

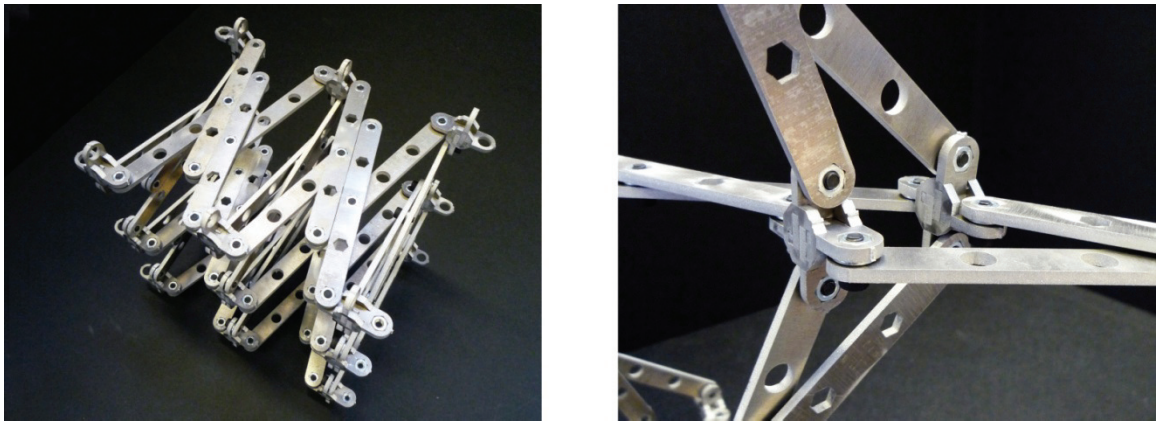
Thicknesses have been incorporated into a digital model to design the parts for physical fabrication. Additional constraints are considered, such as the problems of overlapping, pivots and tolerances. Figures 7 and 8 show the physical prototype that has been fabricated in 1/8" aluminium. Each rigid and straight part is 12 cm long and 12 mm wide, the complete prototype is approximately 16 x 14 cm in its retracted position and 40 x 4 cm in its deployed position. A water-jet cutter has been used to machine the parts, which have then been manually assembled using ball-bearing and screws for each pivot assembly. The rigidity of the parts and the smooth rotation of ball bearings are important to assure the single-degree of freedom of the mechanism, the single actuation and the synchronized propagation of movement from one component to another. The working prototype is a proof that supports and confirms the initial geometrical discovery of the double scissor-pair component, now in the physical world.



[fig. 6] Double scissor-pair three-dimensional array

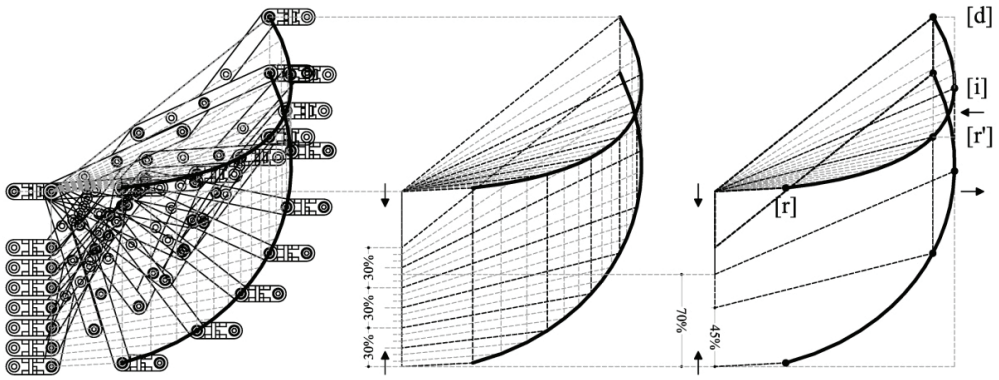


[fig. 7] Double scissor-pair physical prototype



[fig. 8] Double scissor-pair physical prototype (detail)

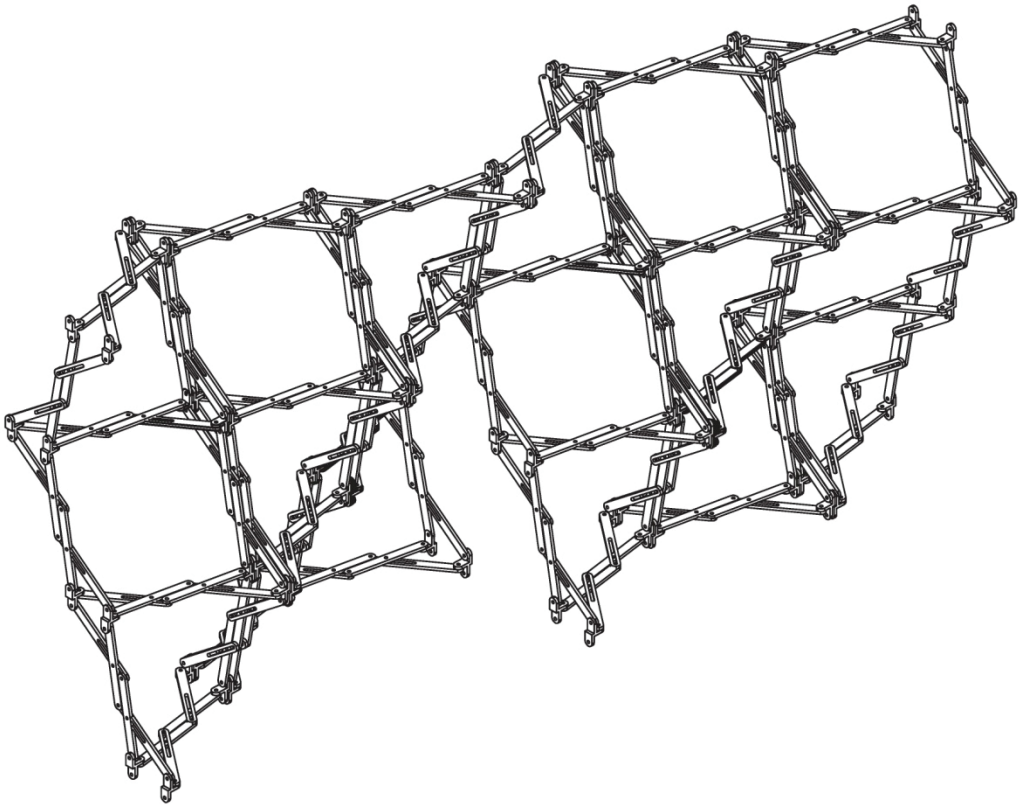
Even though real-world behaviour has been predicted through parametric model simulation and analysis, the physical prototype displays a strange behaviour in the last states of deployment. The behaviour changes drastically after approximately 70% of deployment. Figure 9 demonstrates this particular process. It is possible to appreciate the path described by one double scissor-pair throughout transformation: From the retracted state [*r*] towards the in-between state [*i*] the pivots move in a positive direction, describing a predictable slope variation; yet after [*i*] towards deployed state [*d*] the process changes drastically: the pivots move in a negative direction, developing an extreme slope modification. In spite of this unexpected and novel type of transformation, the double scissor-pair physical prototype maintains the single-degree-of-freedom advantages of previous scissor-pair solutions: it offers a non-uniform and surprising transformation—and, therefore, a range of alternative shapes—physically in three-dimensional space and with single actuation.



[fig. 9] Non-uniform transformation of the double scissor-pair component

As shown in figure 10, the double scissor-pair aluminium prototype is able to transform its shape in a vertical configuration. This transformable three-dimensional structure can be envisioned as an architectural element: a vertical partition able to change its shape and generate indeterminate separations among spaces. Figure 10 shows how the vertical elements of the structure can be considered as two double scissor-pair components producing an additional behaviour: during transformation the system may allow modular disconnection generating

structural discontinuity, fissures and openings. This new capability may add interesting architectural possibilities to the system: the process of transformation would not only divide and delimit space, according to different shapes, but also would enable a variety of fissures to be opened and closed by the users.



[fig. 10] Architectural application: Transformable partition

02_Enabling the Choice

User's Choice

Indeterminate buildings could be conceived as live structures that transform their shapes according to a process of mutual interaction with their users. Within this vision, the building corresponds to an ambiguous, malleable and initially purposeless environment defined partially by the designer and partially by the user. The designer proposes a range of possible solutions enabling the *users' choice*, according to incidental and variable individual and collective needs, demands and desires. Both sides of the equation are needed: the final shape is the result of this mutual and continuous interaction between the possible solutions offered by the designer and the selection of some of them by the user.

According to Archigram the design of indeterminate buildings, which offers a *range* of possible solutions, enable the users' *choice* according to incidental needs, demands and desires. In a manifesto proposed in 1966 Peter Cook invites the user to be an active agent in the

definition of the building, by stating: *what you want when you want* [25]. For Archigram, the determination of the built environment is no longer left in hands of the designer of the building but rather it turns to the users, enabling them to choose what they want whenever they want: "Architecture can be much related to the ambiguity of life. It can be throw-away or additive; it can be ad-hoc; it can be more allied to the personality and personal situation of the people who may have to use it" [26].

In that sense, indeterminate buildings could be designed as machines that interface between the environment and the users. Archigram uses theories and technologies proposed by Cybernetics, defined in 1947 as the scientific study of control and communication in the animal and the machine [27]. Archigram's *Control and Choice* project, proposed by Peter Cook and Ron Herron in 1967, exemplifies how the cybernetic vision is translated to the control of buildings in real-time according to the input/output machine's capabilities. The *Control and Choice* project is a responsive mechanism composed of a tartan grid of tracks, which enabled the delivery of different services when needed. However, more interestingly, this responsive mechanism is covered by a rippled skin able to expand and contract according to the internal pressures, the movement of the deliveries and the users' demands.

Similar to Archigram's notion of buildings as cybernetic machines, Zuk and Clark consider buildings as responsive mechanisms able to transform kinetically [28]. They relate several ideas, developed in the sixties in construction, engineering, robotics and aerospace, which implied the control of a certain transformable behaviour through mechanical movement and sensory-motor capabilities. For Zuk and Clark, architecture can be defined as a "three-dimensional form-response to a set of pressures" and, therefore, kinetic architecture corresponds to the shape modification according to the change on these pressures [29]. In this case, the input corresponds to these set of pressures, and the outputs to the shapes, within the range of alternatives, enabled by the transformable building.

According to Zuk and Clark, future change cannot be completely predicted or predetermined during design conception, and a kinematic architecture, based on movement, variation and control, will be partially the product of chance [30]. However, the range of possible solutions offered to the user is still restricted by the input/output capabilities of the building-machine. The users can only chose within a fixed and predefined range, wherein the building is not an indeterminate machine but rather a predetermined and predictable one, because it offers the same output according to the same input. Even though, the design of transformable structures offers a range of possible states to be chosen freely by the user, it is not possible to change the behaviour of the machine once built. In other words, the users cannot program the type of behaviours, the input/output relation, as they want whenever they want.

Learning from the Real-World

Instead of predefining the behaviour of the machine, some *Artificial Intelligence* (AI) theories and techniques show how this behaviour can be defined by interfacing with the environment in real-time. In these approaches, the theoretical understanding of the real-world phenomena is assumed as incomplete and uncertain and, thus, neither predictive nor simulation models are used. These AI theories and techniques extend machine control to artifacts in which the relation

between input and output is not fixed and can be defined and redefined in real-time without preconceived representations of the world. Even though these theories and techniques have been used in AI to engineer complex robotic systems, they have great potential when applied to simpler architectural machines able to change their behaviour in real-time according to emergent situations.

In the paper *Intelligence without Representation*, Rodney A. Brooks proposes the concept of *Subsumption Architecture*: a methodology of tasks decomposition in which multiple goals are organized in layers, with neither central representation nor preconceived models of the world [31]. Brooks proposes autonomous robotic agents called *Creatures* which have to be designed to cope with changes in their environment and adapt to fortuitous circumstances. For him, it turns out to be better "to use the world as its own model" [32], and therefore instead of predefining the overall behaviour, Brooks lets the Creature simply move around and interact with its environment through perception and action. For example, an initial layer can be used to *avoid* unexpected obstacles the robot may encounter in the environment, using sensors to detect obstacles and motors to turn and move in another direction. Another layer can be added to *explore* by looking at distant places and trying to reach them, using the same sensors and motors in parallel with the previous layer. An interesting observation here is that the Creature behaves—avoids and explores—without having a pre-defined representation, by simply interfacing with the world through perception and action. Likewise, each activity is an incremental layer of intelligence, which in parallel achieves different goals at the same time.

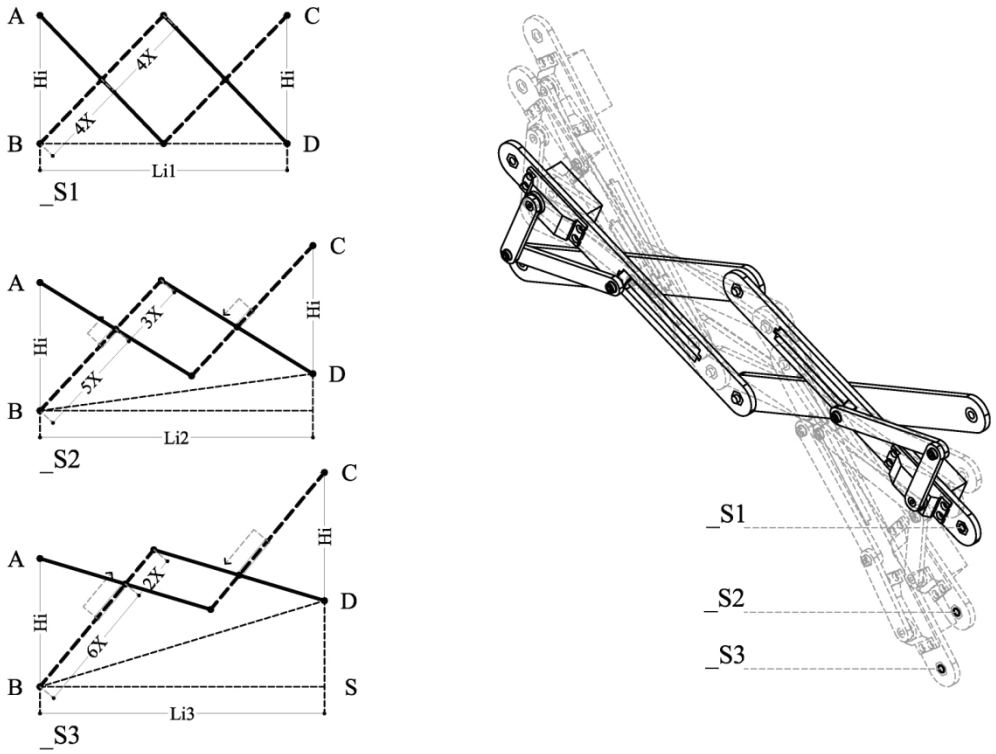
Learning by Recording Cases is another AI technique that considers real-world phenomena to be uncertain, and therefore the system is designed to self-sense, learn and enhance its behaviour by practice. Learning by Recording Cases is a technique that has been applied to the design of task-level robots to move an arm, swing a pendulum and throw or juggle a ball [33]. In these systems, the torque variation for each actuator is unpredictable, and therefore the actuations are not predefined and instead are learned through practice [34]. For example, a robotic arm moving along a given trajectory illustrates how a system can learn by recording its own behaviour and according to real-world factors. The robotic arm begins with random and erratic movements. Consequently, data is recorded and then related to the desired trajectory. *Learning Algorithms* are used to make classification and predictions and then, by iterating the whole process, the system is able to progressively improve its performance reaching a satisfactory result [35]. The robot is designed for indeterminacy through setting up a system able to define and re-define its behaviour in the real-world through practice.

The concepts of Subsumption Architecture and Learning by Recording Cases illustrate how to envision indeterminate machines that remain in an open-ended process of definition and redefinition through time. This radical approach can be extended to the design of indeterminate *buildings-creatures* able to change their shapes and behaviours according to emergent situations. While Subsumption Architecture can be applied to simple sensory-motor architectural components that work in parallel and that perceive and act according to users' incidental needs, demands and desires, Learning by Recording Cases can radicalize that process through enabling permanent learning and even overriding and re-programming the machine's behaviour in real-time.

Experiment 02: Changing the Transformations

The double scissor-pair component offers a range of possible solutions that enable the users' choice: A variety of possible non-uniform shapes controlled by single actuation. This great advantage of single actuation, nevertheless, represents a restriction since only one type of transformation is possible. Even though the double scissor-pair allows a non-uniform space of possible solutions states, the transformation is predetermined since the same input generates the same output. It is not enough to offer a fixed space of possible solutions, but also to enable the user to choose what type of transformations the systems would produce. In order to radicalize the indeterminacy of scissor-pair transformable structures it is necessary to incorporate additional degrees of freedom to be controlled by sensory-motor actuation.

The centre and off-centre solutions can be related by incorporating an additional degree-of-freedom to the double scissor-pair solution. Actually, the off-centre component corresponds to the modification of the scissor-hinge from the centre to off-centre position. Therefore, by considering that modification as a slider, the double scissor-pair component would be able to transform from centre to off-centre position and vice versa. This actuated double scissor-pair solution emerges from combining the centre and off-centre solutions, wherein both are basically two states within a range of continuous transformation [36]. Figure 11 shows these in-between states—S1, S2 and S3—and the physical actuated double scissor-pair component as well.



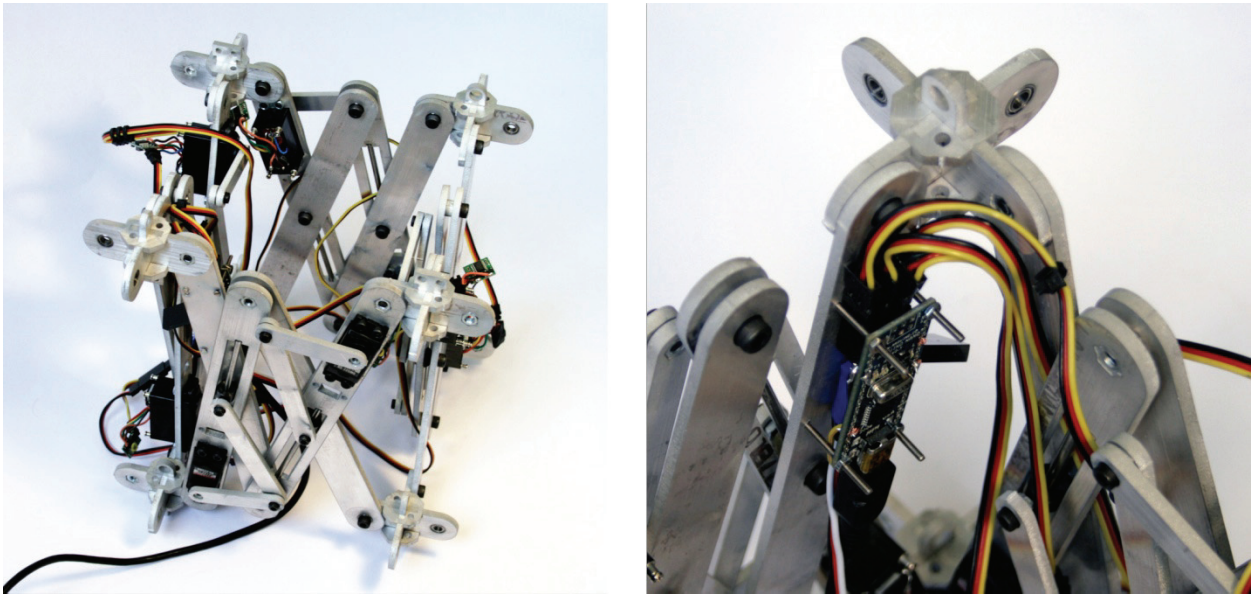
[fig. 11] Actuated double scissor-pair component and in-between states S1, S2 and S3

Since the double scissor-pair solution is actually two off-centre components, it is necessary to incorporate two linear actuators. The objective here is to generate new shapes and behaviours in real-time, extending the design process to the real-world. Therefore, the system has to be capable of being programmed and reprogrammed in real time through sensing human input and reproducing it as physical output. According to those capabilities, the system has to fulfill the following requirements:

A-Sensing: In *passive* mode, the motors have to work as sensors to record the rotation, defined by the user in real-time.

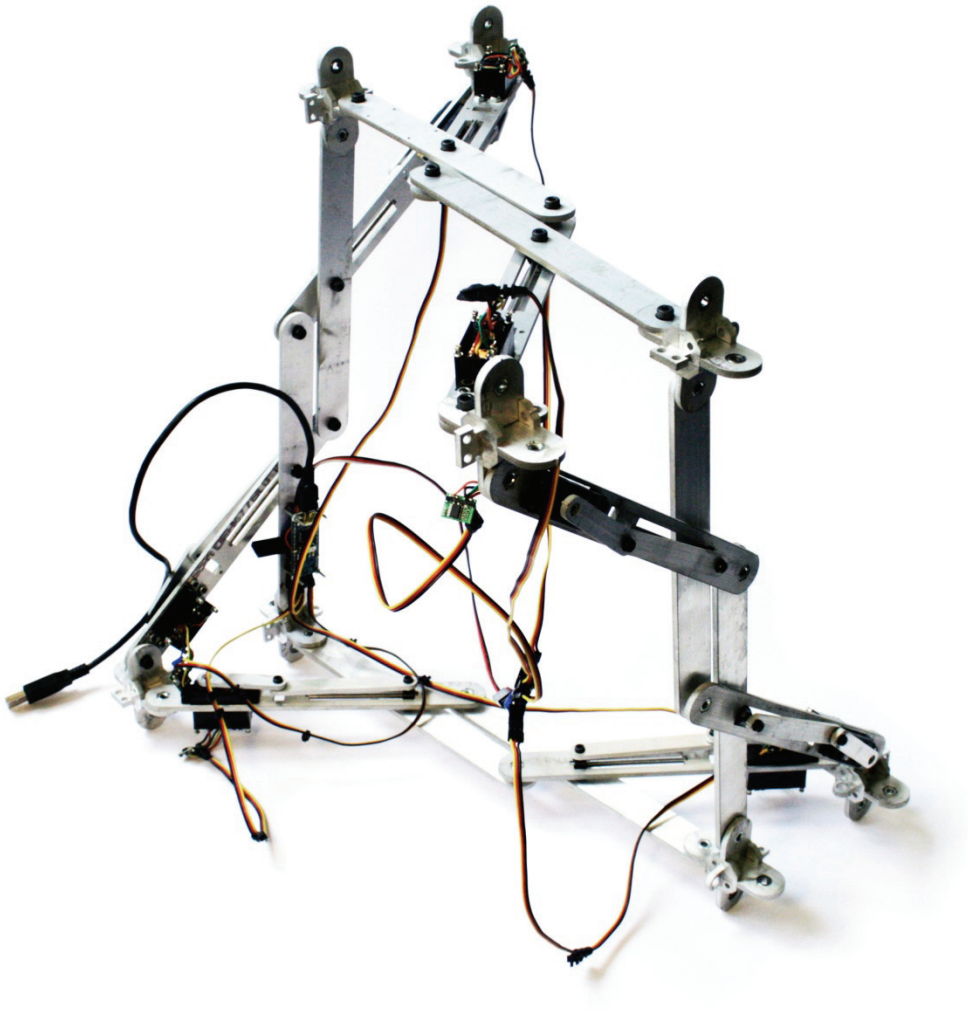
B-Actuating: In *active* mode, the motors have to reproduce the transformation, recorded throughout the sensing process.

C-Processing: The relation between *passive* and *active* mode has to be overridden and reprogrammed in real-time.



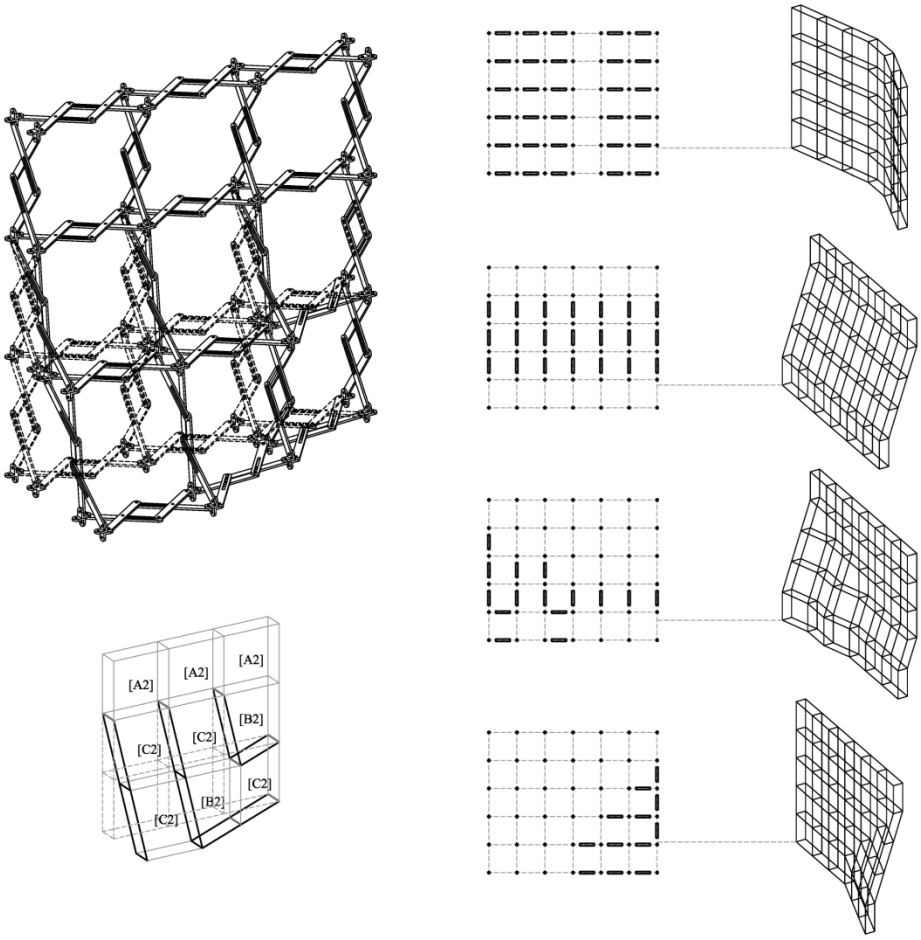
[fig. 12] Physical Model: linear servo mechanisms controlled by an *Arduino*

A servo mechanism is used to fulfill the requirements of sensing and actuating by connecting a servo motor to a two-member-linkage and a sliding member. This system works as a linear-servo actuator that uses the servo's internal potentiometer to sense, and the servo's DC motor to actuate. This processing operation is controlled by an *Arduino* microcontroller that is embedded in the structure [figs. 12 and 13]. Even though a traditional servo motor works, by default, in active mode, the linear-servo actuator is capable of sensing during passive mode as well. The scissor-hinge's position can be modified in real-time since, during passive mode, the DC motor is turned off, and using the internal potentiometer to sense the rotation and to use that data as input.



[fig. 13] Physical Model: S3 in deployed position

Through the assembly of the *actuated double scissor-pair* component it is possible to generate new types of two-dimensional and three-dimensional *scissor-pair transformable structures*. Now, since there is an additional degree-of-freedom, which is controlled through the linear-servo actuator, it is possible to follow alternative states with no unique transformation. The transformation is no longer single-valued due to its capability of following multiple trajectories or lines of behaviour. In figure 11, it is possible to observe that the in-between states S1, S2 and S3 have the same in-between height Hi. This property is fundamental for three-dimensional assembly, since it will enable the combination of different states, in different directions, and, more importantly, the partial actuation of the structure. Figure 14 shows that certain behaviours require more actuation than others. The designer may want to optimize a certain number of actuators, allowing the system a certain degree of uncertainty. In this case, the advantage is that less actuation generates a double curved configuration, which may be aesthetically interesting for the designer and the user [37].

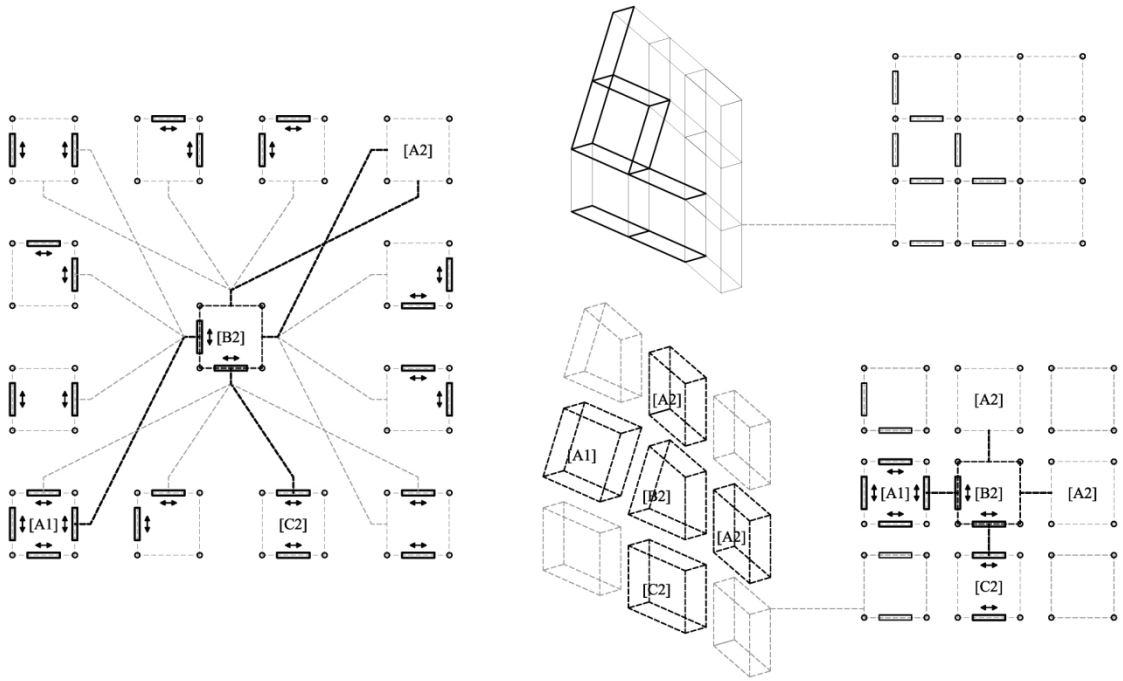


[fig. 14] Partial actuation and different type of transformations

Nevertheless, the structure is a closed-chain mechanism [38] and, therefore, there is a problem of three-dimensional combination and coordination of the different actuations in parallel. However, instead of modeling, predefining and restricting local actuation and overall behaviour beforehand, the *Learning by Recording Cases* technique is used to learn from the interaction between mechanical constraints and user input: the double scissor-pair components are organized in independent modules, which are then programmed to sense, record and learn from the real-time input defined by real-world constraints.

Likewise, the *Subsumption Architecture* method is used to coordinate the relation between local input-output processes. Figure 15 specifies how the components, organized in modules A1, A2, B2 and C2, can be considered as individual *Creatures* able to work independently, yet in response to their neighbors. Each module has four sides, wherein actuation may or may not be applied. The constraint is that this behaviour, the actuation of each module's side, has to be coordinated to perform overall transformation. The central module B2 is chosen to illustrate this constraint process. Figure 15 demonstrates that for each B2 side, there are four possible corresponding states. Therefore, if the central module is transformed from A2 to B2 there are only 4 possible neighbors per side offering 16 possible alternatives to be combined. This process can be explained as a constraint propagation problem in which the definition of one state defines certain alternatives, which likewise, once chosen, requires running the process

again, in a recursive way. Therefore, even though the goal of overall transformation is indeterminate, the process can be reduced to the behaviour of one chosen module, in this case the central module that transforms from A2 to B2.



[fig. 15] Sensory-motor control using constraint propagation

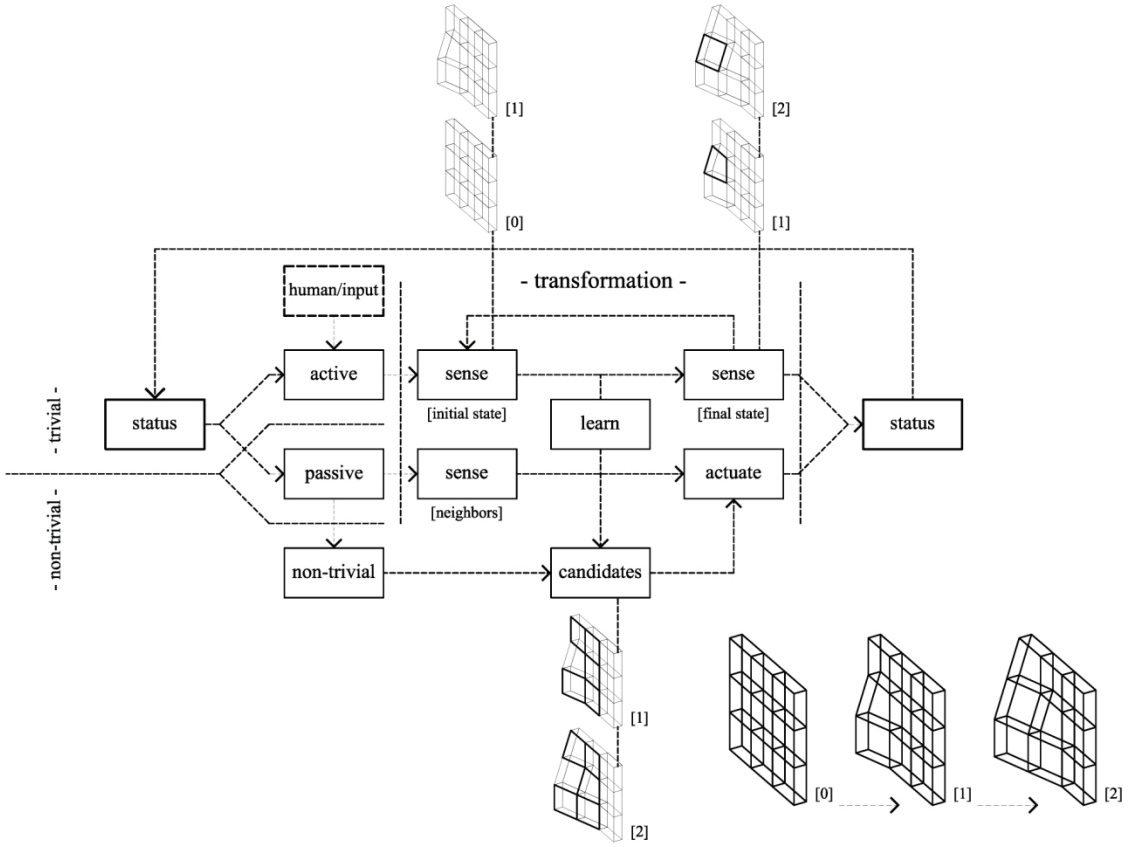
This approach is important since the objective is to respond locally according to users' input in real-time. The notion of the system as a decentralized modular robotic structure enables the generation of overall behaviour through local interaction with the user in real-time. The shapes and behaviours are uncertain for the designer, who is only responsible to set up a system capable of being defined and re-defined by the user in real-time. Indeterminacy is addressed through the task decomposition method, according to two tasks, organized in parallel layers, as follows:

A-Trivial behaviour: Responds to users' expectations, behaving according to the demands in a predictable way. In this case, the user gives some inputs and, after observing the outputs, is able to predict how the structure is going to transform.

B-Non-trivial behaviour: Does not respond to users' expectation, behaving in unpredictable ways in order to promote unexpected outcomes. In this case, the user is not able to understand how the structure works and therefore, for the user, the transformations are always new [39].

What must be noted is that the first layer, the trivial machine, is the default mode, and that the non-trivial mode only operates when the user is willing to obtain indeterminate outcomes. Figure 16 explains the process of activity decomposition in robotic scissor-pair transformable structures. The diagram shown in Figure 16 is based on constraint propagation, explained in Figure 15. Each module has to process the loop independently since the system is locally controlled by a microprocessor. There is no central control and the modules operate

according to the user's input, during *passive* mode, and according to their neighbors during *active* mode.

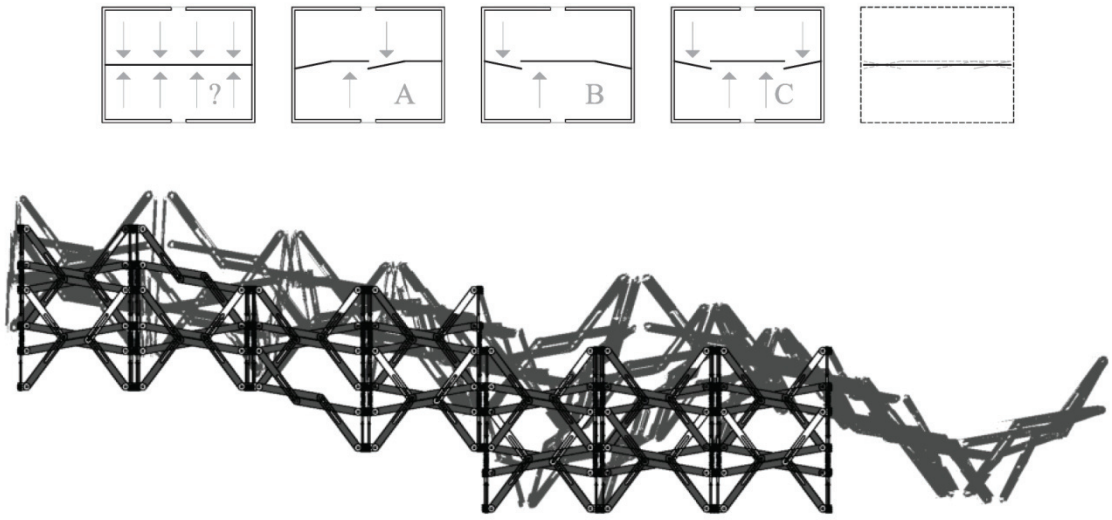


[fig. 16] Activities in parallel: trivial and non-trivial behaviours

The process launches in a trivial mode by checking the status of a module. If there is human input, the system is set in passive mode, wherein actuators are turned Off in order to sense the transformation from state [0] to state [1]. Otherwise, the system is set in active mode and through the constraint propagation, explained in Figure 15, the system has to find a proper module candidate and actuate accordingly. In the beginning, the system will choose arbitrarily, and may appear erratic to the user. Yet through practice, the system will learn what types of states are chosen by the user and likewise how to optimize the number of actuations. Nevertheless, this learning process may be overridden every time the user is willing to get unexpected shapes and behaviours. By activating the non-trivial mode, the possible candidates are, again, modified arbitrarily. Likewise, because the human input is applied locally, the non-trivial behaviour may emerge in other regions of the structure and not necessarily in neighbouring modules.

The arrangement of the double scissor-pair components in modules enables disconnection and structural discontinuity, creating a range of possible indeterminate openings and connections between both sides of the structure. However, with sensory-motor actuation the shape and position of the fissures are not predetermined nor fixed anymore. Now, instead of deciding the final shape of a vertical partition and the location of the openings and connections between one side and the other, it may be possible to define a range of possibilities and different ways to open

and close the structure as a whole: a malleable and indeterminate partition that can be opened, closed and changed with need, according to functional and aesthetic criteria controlled and chosen in real-time [fig. 17].



[fig. 17] Architectural Application: Sensory-motor indeterminate partition

Conclusions

The objective of this paper was to convey the uncertainty that designers confront about the future situations their designs may encounter and may produce once built and throughout time. The vision was proposing the design of indeterminate solutions. Instead of designing unique fixed and ideal solutions, the new direction proposes transformable environments able to offer a range of alternatives to be defined and redefined by the users in real-time: An indeterminate architecture, sympathetic to uncertainty, incompleteness and emergent situations, wherein the building is reduced to an ambiguous, ephemeral and almost immaterial building environment.

It was argued that the design of an indeterminate architecture was the result of extending the design process to the real-world, by designing a range of alternatives to be selected in real-time by the users. The paper was organized around these two main ideas: *Designing the Range* and *Enabling the Choice*. For each section, a theoretical background about indeterminate architecture is presented—to introduce the concepts, problems and directions—followed by a technical background, involving engineering and AI methods—to materialize and radicalize indeterminacy—and an empirical experiment—to propose some novel architectural applications.

As regards the theoretical background, while Archigram's ideas and projects explained the origin of indeterminacy and showed some radical architectural applications, kinetic architecture expressed the advantages and limitations of an indeterminacy fostered by the design of transformable buildings. In relation to the technical background, while some engineering solutions demonstrated how to materialize a range of states by using scissor-pair transformable structures, some AI methods illustrated how to radicalize users' choice by machine control in real-time. Existing scissor-pair transformable solutions were analyzed by exploring the in-

between states, the range of possible shape within the transformation. Subsumption Architecture theory and Learning by Recording Cases technique demonstrated how a machine could interface directly with the real-world, without predetermined representation, and how it could self-sense, record and learn from its own performance and interaction with the world. Finally, the empirical experiment used the architectural and technical background to explore the boundaries of indeterminacy within architectural design. The experiment aimed at radicalizing indeterminacy as much as possible, by searching for non-uniform transformations, to extend the range of possible solutions, and for techniques to enable the user's choice and modification of the machine's behaviour in real-time. A novel scissor-pair component was presented along with the digital and mechanical system to radicalize its indeterminate capabilities.

Even though the theoretical, technical and empirical work was successful in stating the problem, showing initial answers, direction and applications, there are some ends yet untied that are valuable in delineating the scope of future research. First, the theoretical background referred only to the origins of the concepts and ideas within a limited framework. Future work will be conducted to incorporate additional concerns such as the problem of continuity from conception to materialization. Designing an indeterminate architecture, as a continuous process from design conception to the life of the building, has to redefine the traditional architectural gap between what is designed and what is then built and used.

Second, even though the technical background offers an initial insight into mechanical transformation and actuated control, the way in which these processes should be translated into architectural applications was not clearly stated. It is important to find proper ways to interact with the building environment and, likewise a proper timescale for the transformation. Future work will be undertaken to study human-machine-building interaction, and how the scale of a building may imply a speed of transformation similar to the one in natural processes, such as seasonal transformations in trees, sea tides, sun, or cloud movements.

Finally, the empirical experimentation with sensory-motor control was not completely implemented. It is still necessary to find a proper way to actuate a structure with economy of actuators, and to implement the software aspect through the use of learning algorithms and layering control. Likewise, the exercise only resolves a particular application within the restricted framework of scissor-pair solutions. It is necessary to propose general deliverable principles to be applied in other types of transformable solutions. The empirical experiment will not be a contribution if it is not possible to use its principles in other explorations. Therefore, there is a need for further investigation into how this particular experiment can define general principles and solutions beyond its own particular technical problems and theoretical implications.

References

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[2] Simon Sadler, *Archigram Architecture without Architecture* (Cambridge: MIT Press, 2005).

[3] William Zuk and Roger Clark, *Kinetic Architecture* (New York: Van Nostrand Reinhold, 1970).

[4] Robert Kronenburg, *Flexible: Architecture that Responds to Change* (London: Laurence King Publishers, 2007).

[5] Non-uniform behavior refers, in the context of this paper, to transformations wherein the in-between states correspond to different shapes. A uniform behavior, on the contrary, refers only to transformation wherein the in-between states are scaled versions of each other.

[6] Sadler, op. cit., p.94.

[7] Peter Cook. *Archigram (*New York: Princeton Architectural Press, 1999).

[8] Sadler, op. cit., p.89.

[9] Zuk and Clark, op. cit., p.11.

[10] Zuk and Clark, op. cit., p.98.

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[13] Charles Hoberman, Radial expansion/retraction truss structures (US patent no. 4942700, 1990).

[14] For movable theatre structures, see: Emilio Perez Pinero, Three Dimensional Reticular Structure (US patent no. 3185164, 1965)

[15] For expandable space structures, see: F. Escrig, 'Expandable space structure.' *Internation Journal of Space Structures* (1985), pp. 79-91.

[16] For collapsible portable shelters, see: Theodore Zeigler, Collapsible Self-Supporting Structure (US Patent no. 3968808. 1974).

[17] For deployable domes see: Hoberman, op. cit. and You and Pellegrino, op. cit.

[18] For retractable roof structures, see: Thomas Buhl , Frank Jensen, and Sergio Pellegrino. 'Shape Optimization of Cover Plates Retractable Roof Structures.' *Computers and Structures* (2004), pp. 1227-1236.

[19] For **centre scissor-pair** solutions, see: G. Edwards, Expanding apparatus for fire escapes (US Patent 415667, 1889); G. Luckey, Nesting three dimensional lazy tong structure (US Patent no 3672104, 1972); and

[20] For **off-centre scissor-pair** solutions, see: F. Escrig and J.P Valcarcel, 'Geometry of Expandable Space Structures.' *International Journal of Space Structures* (1993), pp. 79-91.

[21]For **angulated scissor-pair** solutions see: Hoberman, op. cit. and You and Pellegrino, op. cit.

[22] For more detail see: Rosenberg, op. cit.

[23] This **double scissor-pair** solution is novel because it transforms from planar to double-curved three-dimensional structures while deploying. Other double scissor-pair solutions are intermediate elements that enable the deployment of single curved profiles. See: Z. You, 'Deployable Structure of Curved profile for Space Antennas.' *ASCE Journal of Aerospace Engineering* (2000), pp. 139-143.

[24] For details on the experimental modification of scissor-pair solutions, see: Daniel Rosenberg, 'Novel Transformations of Foldable Structures.' *CAADRIA: Between Man and Machine* (2008).

[25] The statement *what you want when you want* appears in a cartoon made by Peter Cook in 1966 to explain the *Control and Choice* ideas. See: Cook, op. cit., pp. 68-69.

[26] Peter Cook, *Experimental Architecture* (London: Studio Vista, 1970), p. 67.

[27] Norbert Weiner, *Cybernetics* (New York: John Wiley & Sons, 1948). It is important to clarify that the translation of Cybernetics to the control of buildinsg in real-time does not refer here to recent developments in *Intelligent Buildings*. Rather, this translation refers here to the control of kinetic buildings able to change their shape according to variable demands. For information on *Intelligent Buildings*, see: Derel Clements-Croome, *Intelligent Buildings: Design, Management and Operation* (London : Thomas Telford, 2004).

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[29] Zuk and Clark, op. cit., p. 5.

[30] Zuk and Clark, op. cit.

[31] Rodney Brooks, 'Intelligence without representation.' *Artificial Intelligence* (1991), pp. 139-159.

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[35] Aboaf, op. cit.

[36] Rosenberg, 2009, op. cit.

[37] It is important to clarify that the additional degrees of freedom are activated locally and do not necessarily affect the whole structure. Likewise, the scissor-pair's property of single-degree-freedom is not lost, as it is used once a particular proportion between x and y is defined and momentarily fixed by the local actuation.

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