Free-form Transformation Of Spatial Bar Structures

Developing a design framework for kinetic surfaces geometries by utilising parametric tools

Hussein Hussein[1], *Asterios Agkathidis*[2], *Robert Kronenburg*[3]
[1,2,3]*Liverpool School of Architecture, University of Liverpool, UK*
[1,2,3]*{H.E.mohammed|asterios.agkathidis|r.h.kronenburg}@liverpool.ac.uk*

This paper presents a design framework for free-form transformation of kinetic, spatial bar structures using computational design techniques. Spatial bar structures considered as deployable, transformable kinetic structures composed of straight, linear members, assembled in a three-dimensional configuration. They are often utilised in portable, mobile or transformable buildings. Transformable systems of spatial bar structures are mostly based on modification of primitive shapes (e.g. box, sphere, and cylinder). Each system is subdivided into multiple members having the same shape, the so-called kinetic blocks. Some diverse precedents made to develop other forms of transformation of these structures with some issues. This research project will investigate how a free-form transformation of spatial bar systems can be achieved, by redesigning the kinetic block in relation to architectural, technical parameters. In order to develop a physical prototype of the kinetic block, and assess its potential in enabling free-form transformation of a spatial bar system, a design framework incorporating parametric, algorithmic and kinetic design strategies is required. The proposed design workflow consists of three main phases: form-finding, stability validation and actuation.

Keywords: *Parametric design, Kinetic, transformable, deployable, Free-form, design strategy*

KINETIC TRANSFORMABLE STRUCTURES

The term 'Kinetic Architecture' has not a clear definition, but it could be described as the design of buildings in which transformable, mechanised structures, are able to change their shape in relation to climate, function or purpose. Kinetic structures consist of transformable objects that dynamically occupy predefined physical space or moving physical objects that can share a common physical space to create adaptable spatial configurations (Kronenburg, 2007).

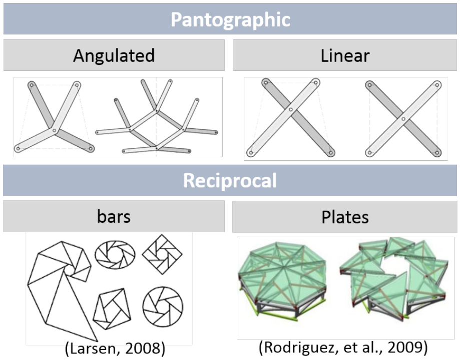
According to Michael Fox (2009), kinetic systems in architectural applications can be categorised into three categories: 'Embedded', 'Deployable' and 'Dynamic'. 'Embedded' systems are the ones that exist within a larger structural whole in a fixed location to control the larger architectural system or a building in response to change. 'Deployable' systems are described as the ones that typically exist in temporary locations and are easily transportable. Finally, 'Dynamic' systems exist within a larger architectural whole but act independently with respect to control of the larger context. Dynamic systems can be sub-categorised into three subcategories: 'Mobile', 'Transformable' and 'Incremental'. The 'Mobile' category includes all types that can be physically moved within an architectural space to a different location. The 'Transformable' category includes systems that can change to take on different spatial configurations and that can be used for space saving and utilitarian needs. The 'Incremental' category includes systems that can be added or subtracted from (e.g. Lego), to create a larger whole out of discrete parts (e.g. metabolism projects) (Fox & Kemp, 2009).

There are some concerns regarding Fox's classification, especially in comparison to the ones made by Gantes (2001), Areil Hanoar (2009), Mazier Asefi (2010), and Esther Adrover (2015). Despite Fox statement that "each of these categories is not mutually exclusive" (Fox & Kemp, 2009), he made a segregation between 'transformable' and 'deployable' structures, which have many common grounds, such as the 'spatial bar structures'.

SPATIAL BAR STRUCTURES

'Spatial bar' structures are considered as deployable, transformable kinetic structures, composed of straight, linear members assembled in a three-dimensional configuration; They share similarities with traditional space frames or space trusses with flexible vertices or intermediate points of their members (Asefi, 2010).

These structures can be sub categorised into two types, *'pantographic'*scissor-pair structures and *'reciprocal'* structures (figure 1) (Asefi, 2010). *Pantographic structures* employ Linear or angulated bars in scissor forms. Reciprocal structures employ even bars or plates mutually supported and placed in a closed circuit (Larsen, 2008). These structures are usually covered by flexible materials (e.g. fabrics, PTFE, ETFE), or rigid materials (e.g. Polycarbonate, Aluminium) with foldable plate mechanism. They are often used in portable, mobile or transformable buildings, being utilised in surface geometries for transformation of interior elements, exterior envelopes or roof structures of buildings (Gantes, 2001), and sometimes used in kinetic sculptures, artworks and space structures (Pellegrino, 2001).



(Larsen, 2008) (Rodriguez, et al., 2009)

Figure 1
Types of spatial bar structures

According to Escrig (2010), these structures occur in six different forms (figure 2), 'Umbrellas', 'Bundles', 'Rings', 'Polyhedral', 'Planes' and 'Double arched'. *'Umbrellas'* have umbrella folding mechanisms and are covered by flexible materials (e.g. Madina Mosque, KSA umbrellas designed by Frei Otto and Bodo Rasch). *'Bundles'* contain modules of scissor mechanisms in planar or spherical shapes (e.g. deployable structures designs of Buckminster Fuller, Emilio Pérez Piñero and Felix Escrig). *'Rings'* contain multi-angulated bars with multiple intermediate joints, deploy towards their central point from the perimeter of the outer circle that they cover (e.g. Hoberman Iris Dome). *'Polyhedral'* bar structures can transform in a spongy way, as it shrinks and expands with respect to its centre(e.g. Hoberman Sphere). *'Planes'* have many pinned bars aligned together forming planar forms (e.g. Santiago Calatrava Milwaukee Art Museum). Finally, *'double arched'* structures, developed by Felix Escrig, can utilise foldable double-arched steel frames as space enclosures.

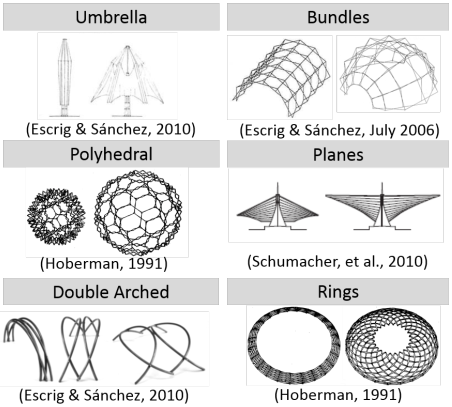


Figure 2
forms of spatial bar structures

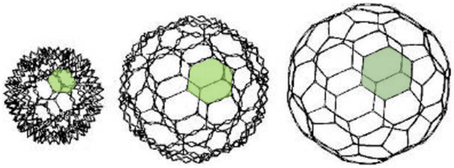


Figure 3
The kinetic building block and its transformation. (Hoberman, 1991)

Throughout the analysis of spatial bar structure types, it has been noted that these structures are based on modification of primitive shapes (e.g. box, sphere, and cylinder). Each system is subdivided into multiple members of the same shape, the so-called *kinetic blocks* (Hoberman, 2006) (figure 3). Modification of each kinetic block leads to transformation of the entire spatial configuration, and its design could be considered as one of the factors affecting the final form of transformation.

EMERGENCE OF FREE-FORM TRANSFORMABLE STRUCTURES.

Zuck and Clark (1970) stated that kinetic systems can be categorised into *'closed'* and *'open'* ones. *'Closed systems'* can change their shape according to a predictable number of needs, in contrast to *'open systems'*, which cannot be completely predicted or predetermined during design conception, they accept modification and addition/subtraction throughout their lifecycle (ZUK & H.Clark, 1970). The lifecycle of a structure depends on its ability to satisfy design needs; the current solutions of spatial structures offer predefined ranges of options with a range of predictable possible states. The process of developing a kinetic motion should consider Ways and Means for operability (Fox & Kemp, 2009). Ways are the kinetic methods by which they perform including folding, sliding, expanding, shrinking and transforming in size or shape. Means, are the impetus for actuation and may include pneumatics, chemicals, magnetism or electrical systems.

There are some newly created precedents of Ways of transformations not listed on the classification by Zyck and Clark. A deployable *'hyperboloid Pantographic structure'* (figure 4) was developed by AE-Lab, Vrije University, Brussel, as a tower or truss like mast for temporary tensile surfaces, to ease its transportation (Temmerman, et al., June 2009). A Deployable *'Hyperbolic Paraboloid'* (figure 5) (i.e. saddle geometry) structure, proposed by Fufu Yang , Jimmin Li and Yan Chen, from Tianjin University, China , and Zhong You from University of Oxford, UK, using Bennett linkages with 1 DOF (degree of freedom), just to widen the deployable structure's geometrical possibilities (Yang, et al., 2015). These solutions are based on folding-expanding mechanisms regardless the actuation means required for transformation.

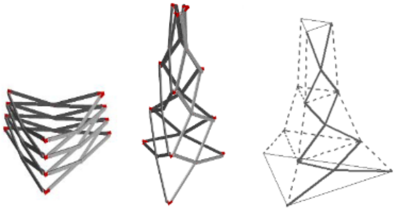


Figure 4
Deployable Hyperboloid pantographic Structures (Temmerman, et al., June 2009)

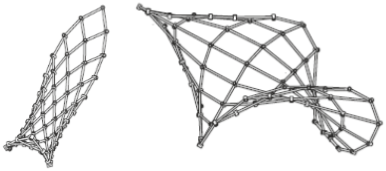


Figure 5
deployable Hyperbolic paraboloid structures (Yang, et al., 2015).

Other solutions proposed free-transformation based on redesigning the linear elements (i.e. 2D framing) and the scissor-pair mechanism itself. Yenal Akgün, in his PhD research at the University of Stuttgart, proposed a redesign of the scissor-hinge by utilising two joints at a specific point in the scissor mechanism and combining it with actuators to obtain unique extensions and rotation capabilities to each scissor (i.e. module) with basic 1 DOF joints (Akgün, 2010). This was to provide adaptive structural surfaces without changing the dimensions of the trusses or the span. He did some digital prototypes of linear elements in one-way (figure 6) and two-ways (figure 7) configurations.

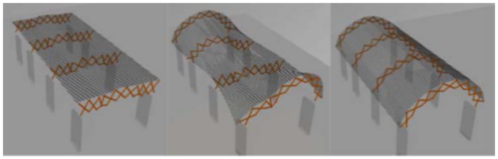


Figure 6
One-way Linear scissor-pair mechanism (AKGÜN, et al., 2007).

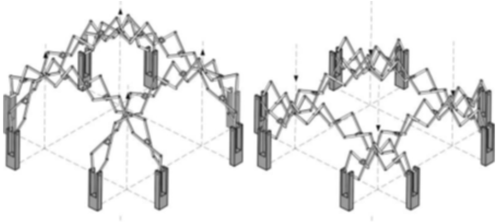


Figure 7
Two-way linear scissor-pair mechanisms (Akgün, 2010).

Daniel Rosenburg, in his master of science research at MIT, proposed some prototypes utilising scissor-pair mechanisms with two off-centre joints with sliders, to control the degree of freedom utilising basic 1 DOF linkages, (i.e. to transform from centre to off-cen¬tre position and vice versa)(figure 8) (Rosenburg, 2009). Despite The solutions offered by these researchers depends on linear elements; they highlighted the effect of changing the basic module (scissor mechanism) on the transformation of the entire system.

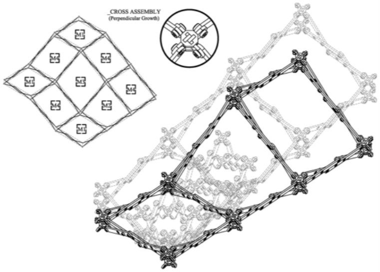
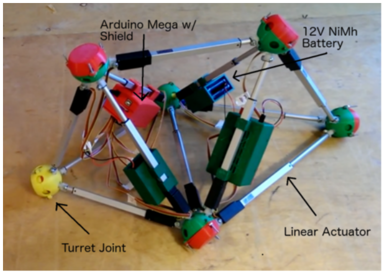


Figure 8
a latticework composed of scissor-pair mechanisms with two off-centre joints (Rosenburg, 2009).

Some researchers proposed solutions for making three-dimensional transformable modules without employing them in structural applications. William Bondin, Francois Mangion and Ruairi Glynn, researchers at BMADE Robotics Lab, Bartlett School of Architecture, UCL, created a project called 'Morphs' [1] (figure 9). It is a robotic mechanism with octahedral structure, which can move around public spaces and respond to its environment; utilising twelve actuated struts that shifts the CG (centre of gravity) of the entire structure.Robert L. Read, a computer scientist and a contributor in Public Invention repository, commenced a project called 'The Gluss' in August, 2015 (announced in September 2016) [2]. Inspired by the 'GEOMAG' toy, he developed 'Tetrobot', a robotic module prototype (figure 10), based on tetrahedral and octahedral geometries, utilising a set of linear servo motors and 3D printed open source 'Turret' joints, invented by Song, Kown and Kim (Song, et al., 2003), aiming to create metamorphic robots. Both researchers utilised joints with two DOFs, employing a large set of actuators that make it expensive; According to Read, the cost of 'Tertrobot' prototype is estimated around £2500 [2].

Figure 9
Morphs robot [1].

Figure 10
The Gluss Tetrobot
[2]

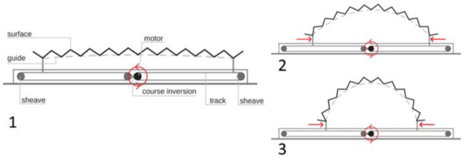


While many researchers proposed solutions based on transforming the 'kinetic block', others proposed solutions based on bending the entire surface itself. In 2014, Jordi Truco and Sylvia Felipe, known as Hybrid architecture, built the 'Hybermembrane' (TRUCO & FELIPE, 2014) (figure 11), a 10 x 20 m prototype, in the 'Barcelona design hub museum'. The structure transforms by hydraulic masts, located on its perimeter, able to bend the elastic structure members connected with universal joints; and it is cladded with elastic materials.

Figure 11
Hybermembrane
installation [3].

Another research team, Filipa Osório, Alexandra Paio and Sancho Oliveira, from the Vitruvius Fab-Lab in Lisbon University, Portugal, proposed a free-form transformation of surfaces by tessellating them with folding patterns (figure 12), placing the actuators horizontally in the surface base (Osório, et al., 2014).

Figure 12
the bending
process of kinetic
folded surface
(Osório, et al., 2014)



Both solutions achieved free-form transformation of surfaces, however, compared to the previous solutions, the resulting surface (i.e after transformation) can not fit a designated form easily nor precisely.

Consequently, we seek to develop a reliable kinetic system for double layered spatial bar surfaces, which enables precise and controllable freeform transformation. This will be attainable by developing a system based one 3D kinetic blocks, flexible joints, fixed bars and a set of actuators, assembled together in a reliable configuration generated by computational design techniques. in relation to architectural, technical or design process related parameters. Considering such parameters in an early design phase could improve the system's transformation efficiency. In addition, investigating surface tessellation techniques in relation to the transformability of each kinetic block could contribute in optimising the number of utilised joints and actuators required to attain the designated transformation. In particular, we will investigate following research questions:

1. What is the relationship between free-form transformation of spatial bar systems and the kinetic block?
2. How does the modification of the kinetic block affect the entire system?
3. How can we achieve a controlled free-form transformation of spatial bar systems, achieving a designated form, by utilising parametric tools?
4. How can we develop an optimised and reliable spatial bar system, composed of multiple kinetic building blocks (i.e. controlling the DOF)?

DEVELOPING THE DESIGN FRAMEWORK

In order to investigate the research questions, we will develop a physical prototype of a kinetic block, and assess its potential in enabling free-form transformation of a spatial bar system. Its development is based on introducing a design framework incorporating parametric and kinetic design strategies.

Parametric design Strategies

Globa (2015) proposed a parametric design strategy based on an iterative endless process, aiming to achieve the optimum solution 'reality check'. Globa describes a design process starting by setting the modelling parameters, followed by interpretation, a digital model, evaluation, leading to data knowledge closing the circle back to reset the modelling parameters (figure 13). Each iteration increases the 'experience' of the evaluation process, which produces data to be used in resetting the modelling parameters.

Hudson (2010) proposed another practice-led research strategy integrating the Knowledge Development Strategy 'kDev', the Knowledge Capture Strategy 'kCap', the Model Construction 'mCon', and the Design Investigation'dInv', finally leading to the construction documents 'cDoc' (figure 14). According to Tedeschi (2014), this iterative process can be attainable by utilising a genetic algorithm (e.g. the Galapagos plugin for Grasshopper).

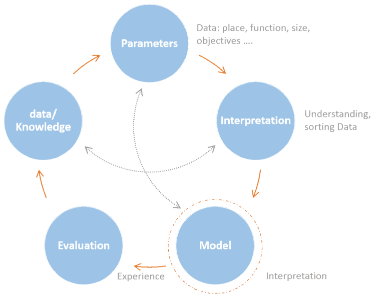


Figure 13 Iterative parametric design loop (Globa, 2015).

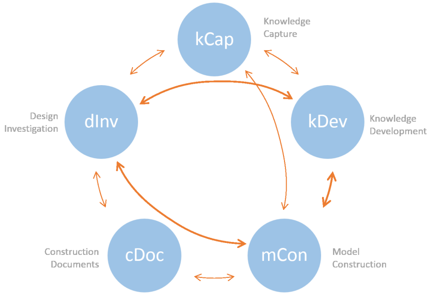


Figure 14 summary of parametric design strategies for practice-led research. (Hudson, 2010).

Kinetic Design Strategies

There are other processes originated in structural and mechanical engineering. Gantes (2001) proposed a kinetic design strategy focusing on a stability check, requiring the following three steps: starting with the geometric design, followed by structural analysis under service loads in deployed state (i.e. after transformation) and finally concluding to structural analysis throughout the deployment process (figure 15) (i.e. during the transformation).

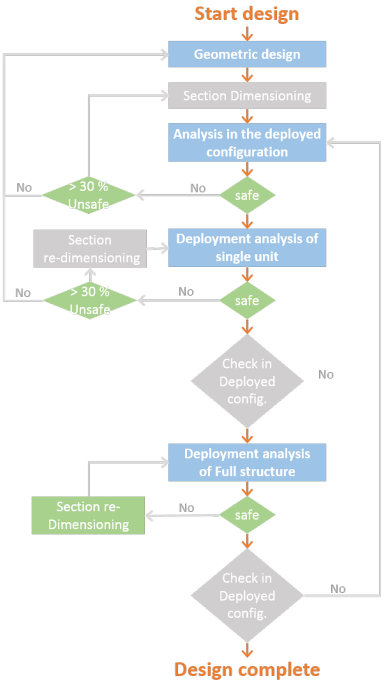


Figure 15 deployable structures design strategy (Gantes, 2001, p. 296)

Wierzbicki (2007) described the mechanical design process of kinetic structures, after reviewing the design requirements and assumptions based on four steps. It can be utilised by starting with a structural component assembly fitting and movement check, followed by covering material components assembly fitting and movement check, a performance check after load simulation, finalised by generating manufacturing and information management data (figure 16).

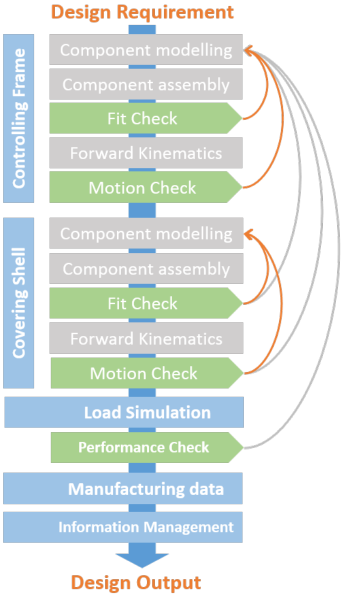


Figure 16
kinetic structures mechanical design strategy (Wierzbicki, 2007)

Finally, originated in an architectural point of view, Asefi (2009) proposed a transdisciplinary design process, focusing mainly in the early design stages. Each step should be reviewed and receive feedback from structural, construction, mechanical, manufacturing and material specialists. The design process, in that proposed design management model, has five outcomes after defining the design requirements (figure 17). First, a *'conceptual design'* phase, proposed by the architect. Second, an *'Initial schematic design'* phase, after defining the structure concept and reviewing it with specialists. Third, *' an advanced schematic design'* phase, after checking the transformable structure compatibility with the basic structure or substructure, and making simulations and tests. Fourth, a *'detailed drawings'* phase, after making prototypes, load simulations, and check the design requirements and specialist contractors. Finally, a construction process after preparing the *construction documents, maintenance program, and assembly tests* (i.e. porotypes) by the manufacturer. Afterwards, *POE* (post-occupancy evaluation) and structure monitoring should be imposed regarding maintenance program to assure the building performance through its lifecycle (Hussein, 2012).

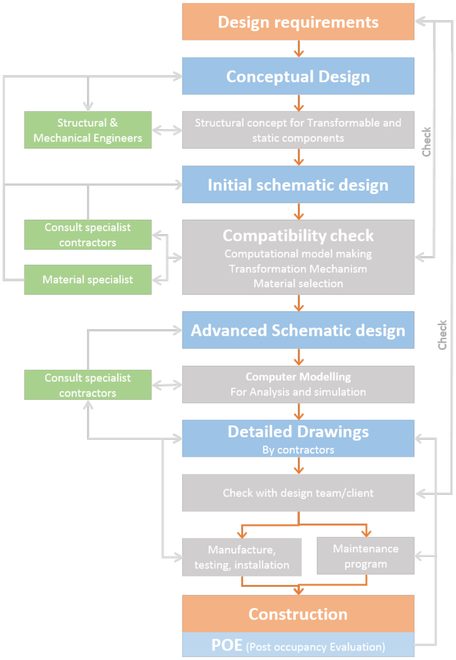


Figure 17
design management model (Asefi, 2010), as edited before by the first author (Hussein, 2012).

Briefly reviewing the existing parametric design strategies, one could argue that they are commonly focusing on generic design processes and it is up to the researchers to tailor a suitable design framework according to their design needs. Moreover, the available kinetic design strategies are mostly focusing on managing problems occurring in non-architectural disciplines (i.e. structural, mechanical engineering etc.). Consequently, we will propose a new design framework in order to build the required prototype of a transformable free-form spatial bar structure.

FREE-FORM TRANSFORMATION DESIGN FRAMEWORK

The proposed design framework is composed of a large set of internal iterative design processes and iterations (figure 19). Summarily, it consists of three main phases: form-finding, stability validation and actuation (figure 18).

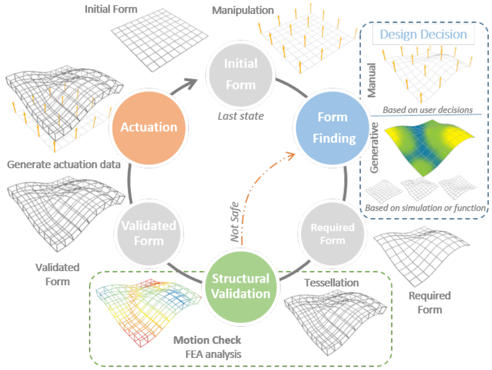


Figure 18
the proposed framework summary

The form-finding phase is focusing on the determination of the exact deformation geometry of the spatial bar prototype. It will operate as a parametric grid system allowing variable types of deformation by defining some manipulators or attractor points. It could either be adjusted to the user's individual preference (i.e. custom edit) or be based on a generative design strategy (e.g. genetic algorithms), incorporating environmental or functional requirements, regarding rules, equations, simulations or sensor data. It will be developed as a parametric model focusing mostly on resolving geometric-kinetic relationships, rather than function related considerations.

In the second phase, after determining the final state of the kinetic block geometry, we will continue with the block's stability validation, according to its actual function (i.e. application) and materiality (e.g. a roof structure, a façade system, a shading device) and the technical data of the structure components (i.e. bars, actuators and joints), (e.g. stiffness, inertia). This will be achieved by using structural simulation tools (e.g. finite element analysis (FEA)). Genetic algorithms (GA) may be applied, to achieve the optimal surface tessellation, which would provide optimum stability for the structure, in the final state and during its transformation. After doing so, a feedback loop will enable redesigning the kinetic block assembly, surface tessellation or the kinetic block itself, in case of the minor issues, or changing the system's components or re-formation of the initial geometry, in case of major issues, to overcome structural efficiency problems before moving to the third phase; the actuation of the physical prototype.

In the final phase, we will proceed to the development of the physical prototype. Its mechanism will consist of linear actuators, linear fixed elements and flexible joints. After the first iteration solution, the fabrication data will be generated based on the technical data of the structure components, previously defined by the user and adjusted by the previous process. Among the most important technical data, required for the actuation process, is the calibration of the linear actuators, in order to determine the relation between the numerical input and the actual movement. Equally important, the mechanical limitations related to the linear movement ranges of the actuators, as well as the angular movement ranges of the joints (e.g. 36 degrees for the turret joint [2]).

The actuation of the physical model will be controlled through the previously defined parametric model, by which the actuation data will be transferred from the computer to the actuator through controllers (e.g. Arduino). The transferred data will derive from a numerical list extracted from a linear actuation motion simulation of the parametric model and will be used as an input to the controller to produce the required actuation.

After the actuation process, the final configuration data will become the initial-form data for another transformation process; that may occur regarding any change of rules or states that impose redesigning of the surface. Afterwards, a database will be created listing each rule, condition, resultant form and actuation data for each transformation process. This will decrease the processing time required for

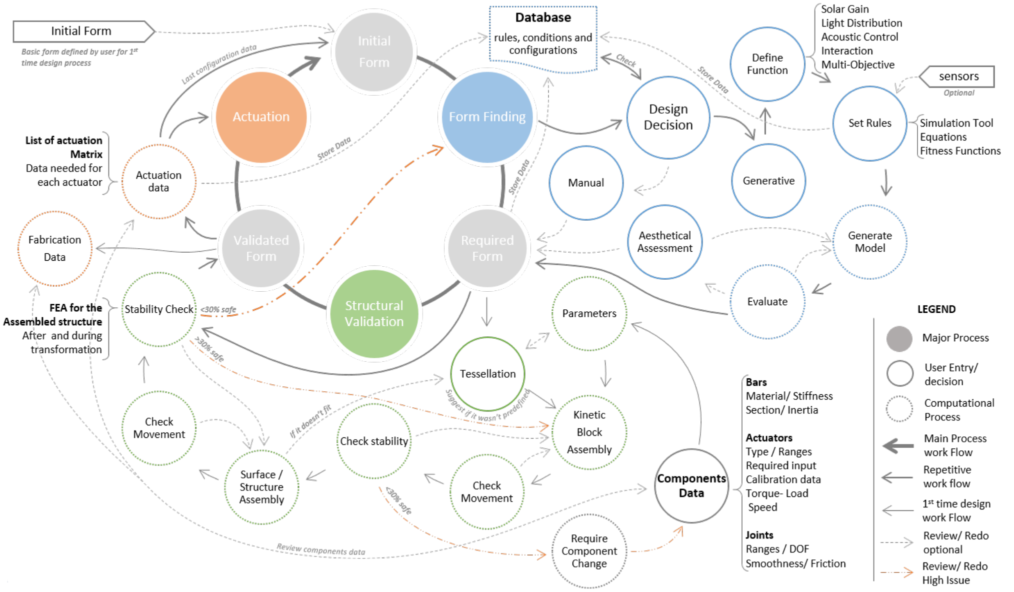


Figure 19
detailed design framework

the form finding process, as the design decision can be stated based on the stored data that match the same rules, states or conditions previously occurred throughout the system operation.

In addition to the user-based, top-down workflow described above, we will investigate a developer-based, bottom-up design approach. While the user based approach is starting by developing the kinetic block based on available components. the developer-based approach will start by designing and calibrating the actuators, followed by designing the linkages and joints and determining their limitations, moving backwards up to the definition of the necessary elements that should be used for the kinetic block. Then, configuring the basic kinetic block, and determining its stability/feasibility, validating its potential and possibilities, assessing the movement gained by transforming it and finally implementing the kinetic block into a spatial configuration (e.g. surface).

This research is still in progress; our expected findings from the following stage include a transformation mechanism and its design framework, which could be applied to different types of surfaces or geometries allowing them to perform free-form transformation movements. That can be employed for some applications and purposes, such as kinetic roofs, transformable ceilings, re-usable formworks, shading devices and other types of applications utilise spatial bar systems.

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