Archi/e Machina: Interactive Architecture Based on Tensegrity

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***Abstract*—This paper elucidates the possibilities of interactive architectural-space. Interactive architectural-space is architectural-space that is changeable or adaptable in interaction with internal and external users and environments. This paper illuminates the point which has not been focused on and describes a methodology of making a prototype of interactive architectural-space to investigate the point. Designed prototype is experimented and evaluated with psychological methods.**

I. Introduction

In this section, background and purpose of this research is described.

A. Interactivity in Contemporary Architecture

Human-beings do various activities involved with architectural-space and architects have designed various architectural-space through history. Modernism architecture is one of the biggest paradigms in architectural design and it seem to still carry on. However, this style of design, built with concrete and glass, is often criticized as design without human embodiment, transformation or development. Our lifestyles, natural environment are changing so drastically that these modernism architectures no longer have the adaptability to them.

Many contemporary architect attempt to solve this problem and create a new paradigm of architecture; Ito's ambient, ephemeral architecture and Kuma's organic-material-based architecture are both at the forefront of it (Fig. 1). These contemporary architectures set ambiguous boundaries between human behaviors and surrounding environments, leaving room for spatial and temporal transformation. In this sense, contemporary architecture can be said as the interactive visualization of the relationships between human and environment.

B. Interactive Architecture by Cybernetics

Cybernetics have theoretically researched on its applications into architectural-space since 1960's. Pask regarded an architectural environment as an adaptive system that developed through controlling users and being controlled by users and illuminated a superordinate interaction in a design process of such system, where the system and its designer control each other[1]. He also presented an idea that an environment analyzes and adapts to patterns of inhabitants' behavior using computer.

Recent advancement in information technology has increased the feasibility of these ideas that could not be actualized because of the limitation in technology and in economic issues. These ideas and theories on cybernetics will contribute to already-described concept of contemporary architecture.

C. Purpose of Research

On this background, many researches on interactive architectural-space that is changeable and adaptable are performed nowadays[2][3]. They deal with various architectural-space in its form, scale, method but all of them attempt to seek and suggest future styles of human beings, architectures, environments.

When we see interactive architectural-space not as reactive mechanical system but as a new frontier of the history of architectural-space, its spatial nature matters; in especially architectural-space that physically moves, the spatial perception of inhabitants will change drastically. Despite that, there is no researches on changes in spatial nature or perception and there is no prototypes that can change and transform whole architectural-space. Purposes of this research is to make a prototype of interactive architectural-space that can move to change its spatial nature and to seek influences by its interaction on spatial experience and perception.

D. Composition of This Paper

In section I, the architectural and cybernetic background and the purposes of this research were described. In section II, relevant researches is introduced to position this paper clearly. In section III, a method adopted to design a prototype of interactive architectural-space is introduced. In section IV, a

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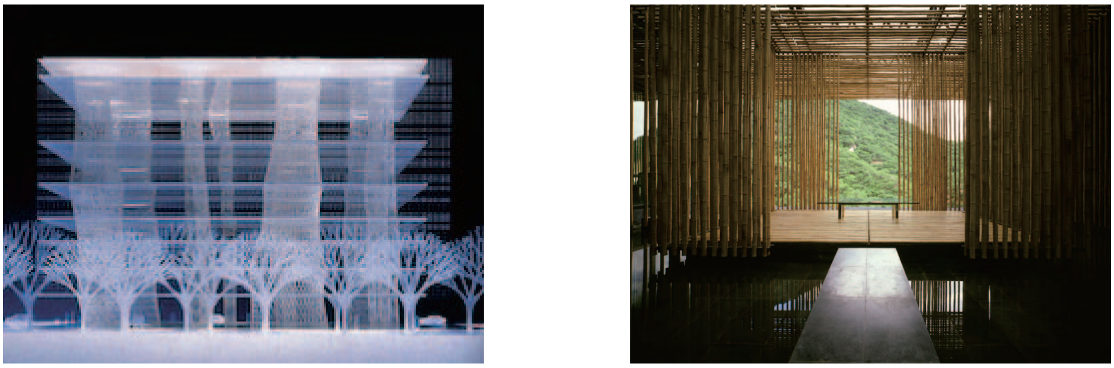


(a) Ito's Sendai Mediatheque (b) Kuma's Great (Bamboo) Wall

Fig. 1. Contemporary Architectures

designed prototype and its specification are described. In section V, experiments on prototype's spatial nature are performed and its result is shown. In section VI, a conclusion and horizons of this research are described.

II. Relevant Research

Section II summarizes existing researches on interactive architectural-space, illuminates the point that has not been discussed by them and positions this research.

A. *Interactive Architectural-space*

In this paper, interactive architectural-space means architectural-space that is changeable or adaptable in interaction with internal and external users and environments. The methods of interaction are implemented in many different ways and this subsection introduces each methods; interaction by audio and visual equipment, interaction by robotics and interaction by spatial movement.

1) Interaction by Audio and Visual Equipment: Interaction by spatial visual equipments has been developed mainly by virtual reality technology and related researches[4]. Recently, based on the widespread of these technologies, many attempts to expand interaction by audio and visual equipments into real architectural-space are performed. The building of Ars Electronica Center, the world's biggest center of art and technology, has $100\mathrm{m}^2$ wall whose whole surface is embedded full-colored LEDs and can transform their color according to real-time control(Fig. 2).

Fig. 2. "LIGHTS ON!" performance by YesYesNo

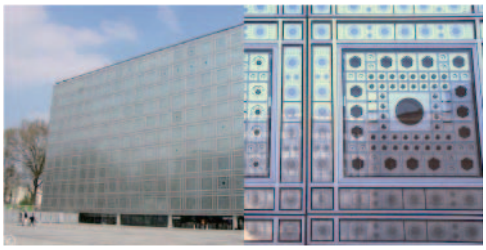
Fig. 3. "Real-World-Showroom" by the Univ. of Tokyo

However, these interactions by audio and visual equipments seem to lack spatial transformability.

2) Interaction by Robotics: According to the definition of robot as machine in which controllers integrated sensors and actuators, there have been many robotics in architectural-space; automatic doors, lifts, automatic lighting equipments etc. Moreover, recent development in robotics enabled more technological robots to enter into our living space, such as cleaning robots, robot pets, surgical robot etc. Using these robotics, Sato and colleagues suggested a concept of "Robotic Room" and its implementation(FIg. 3). They also built up a methodology on interactions between human and machine behaviors in a room equipped with manipulators[5].

But this approach is not to interact with architectural-space itself but to dispose interactive robots or manipulators in existing architectural-space. In this sense, it has a same defect as audio and visual approach.

3) Interaction by Spatial Movement: Robotics is getting so stable as stated and so detail structural analysis is built up that, recently, even architectural-space itself can move and change its spatial nature. It is essential in interactive architectural-space that architectural structures and spatial boundaries interact with



(a) Adaption by movement (Nouvel, xxxx)

(b) Expression by movement (Beesley, 20xx)

Fig. 4. Various movement of interactive architecture

behaviors of users and environments. Fig. 4 shows examples for spatial movement in architectural-space. Nouvel designed "l'Institut du monde arabe" shown in Fig. 4(a). Its wall has geometric patterns that mechanically moves to adjust sunlight from outside into architectural-space. Its gimmicks not only alter lighting condition of the space but also affect on inhabitants' perception of spatial extensity[6]. Fig. 4(b) shows "Hylozoic Soil" by Beesley. This architecture-scale installation reacts human inside and moves a part of post near human. It expresses biotic interaction in its very slow, like sea animal, movement.

This approach has an amount of potential in changing user's spatial perception. Especially, when architectural-space involving human moves in synchronism with movement of inhabitants, it is to be expected that the spatial perception of inhabitants alter drastically. Despite that, existing prototypes or artworks can move only a part of whole space that isn't enough to investigate human perception precisely. A prototype of interactive architectural-space that can interact with inhabitants by moving its whole space has to be created and investigations of its influence on human perception has to be performed.

B. Positioning of This Research

As stated in this section, there are many methods for realizing interactive architectural-space and interaction by spatial movement has a particular potential in influencing spatial perception.

On the other hand, the evaluation of spatial perception in existing architectural-space has been generally performed with Semantic Differential Method (SDM) etc. Jo and colleagues verified the comfortability of personal space with SDM[7]. This kind of researches on psychological influence and design method of architectural-space is called environmental psychology. Maki and colleagues elucidated the entire picture of environmental psychology by describing environmental affordance and becoming personal space of environment[8]. However, these methodology in environmental psychology have yet to be applied to computerized architectural-space.

In this paper, a new prototype for interactive architectural-space that can interact with inhabitants by moving its whole space is introduced and, to evaluate the possibilities of interaction by spatial movement, the methods of environmental psychology are applied.

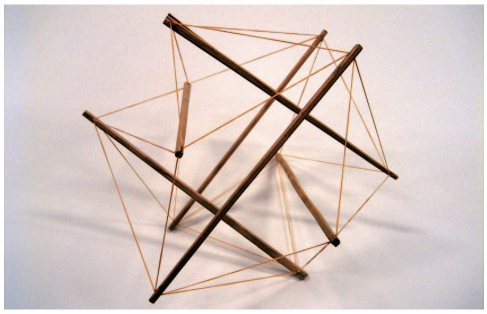


Fig. 5. 6 struts tensegrity

III. Designing Interactive Structure

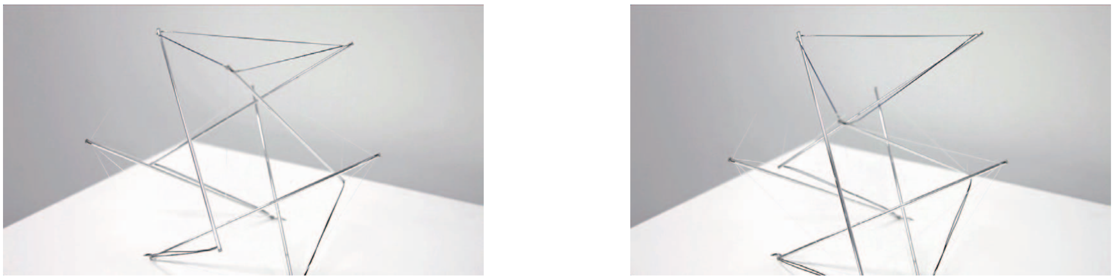
In this section, a methodology of actualize an interactive architectural-space that can change spatial nature and spatial perception by movement. Firstly, tensegrity structure is introduced, that is an adopted structure because of its movability in whole space and its long-term and short-term adaptability. Then, the design of tensegrity structure and its simulation are described.

A. Tensegrity Structure

To evaluate effects of an interactive architectural-space, it is essential that the prototype can move not in a part of the space but in whole spatial structure. This research adopts tensegrity structure for the spatial structure of the prototype of interactive architectural-space. Tensegrity has movability in whole part and long-term and short-term adaptability.

Tensegrity is a structure that was invented 1950's. The definition of tensegrity by A. Pugh is as follows: "Tensegrity systems are spatial reticulate systems in a state of self-stress. All their elements have a straight middle fibre and are of equivalent size. Tensioned elements have no rigidity in compression and constitute a continuous set. Compressed elements constitute a discontinuous set. Each node receives one and only one compressed element"[9]. Fig. 5 shows the most famous tensegrity that is strictly based on the definition and has 6 struts and 24 cables.

Because tensegrity is in an equilibrium state between tensional force and compressional force, it can provide a light, stiff and large space with struts rigid enough to endure compressional force. It has also a spherical network of tensional force



(a) Equilibrated state

(b) Unequilibrated state

Fig. 6. Change in equilibrium state

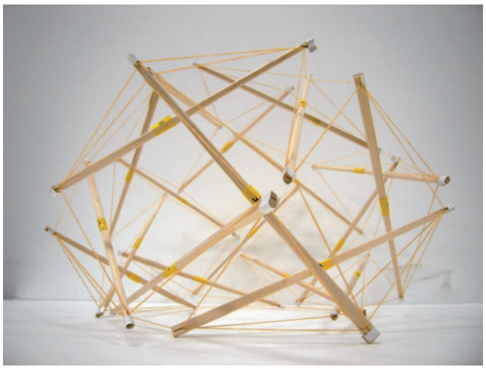


Fig. 7. Designed 21 struts tensegrity dome

TABLE I
STRUCTURAL PARAMETERS OF DESIGNED TENSEGRITY

Parameters	Values
Number of Struts	21
Number of Cables	84
Number of Nodes	42
Cables per Nodes	4
Strut's Length per Cable's Length	1.852

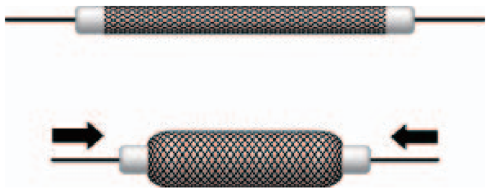


Fig. 8. Diagram of pneumatic muscle

TABLE II
MOTION PARAMETERS OF PNEUMATIC MUSCLE

Parameters	Values
Length at normal pressurs	1.35 m
Length at 0.6 MPa	1.08 m
Generative force	100+ N
Mass	50 g

so that a geometrical change in a small part of the structure, often by change in the length of the component, spread into whole part of the structure(Fig. 6). In this way, tensegrity is suitable for the structure adaptive with human body and with environments.

B. Designing Interactive Structure

This subsection shows the process of designing and verifying the structure of interactive architectural-space. Tensegrity structure of the prototype was designed based on principles bellow:

- Dome shape for spatial extensity enough for user to enter and move around
- Definition based structure for ease in simulating
- Less components for ease in prototyping and constructing

Fig. 7 shows the model of the designed tensegrity and Table I its parameters. This structure is tensegrity with 21 struts and completely based on the definition. Its shape of cut sphere enables users to enter and move around.

C. Actuation

There are several ways to actuate tensegrity and even some robots whose structure is tensegrity. Almost all precedents implement motors on the nodes of tensegrity[10]. However, the motor-approach makes the whole structure very heavy when applied into spatial extensity. Instead, our prototype adopt pneumatic muscle to actuate compressional components of tensegrity because pneumatic muscle is very light but can generate strong force under certain pressures[11]. Fig. 8 shows a diagram of pneumatic muscle and Table II its motion parameters.

D. Simulation

To verify the movement of tensegrity with pneumatic muscles, dynamical simulation was performed using Open Dynamics Engine. Pneumatic muscles are implemented instead of corresponding tensional components. The places of pneumatic muscles are determined according to the tensional force on corresponding tensional components. The more force acts on a component, The more the substitute pneumatic muscle elongates. So tensional components are replaced with pneumatic muscles from the strongest-force-acted one to the weakest-force-acted one as shown in Fig. 9.

The number of pneumatic muscles are decided according to the safe height of collapsing state in which all pneumatic mus-

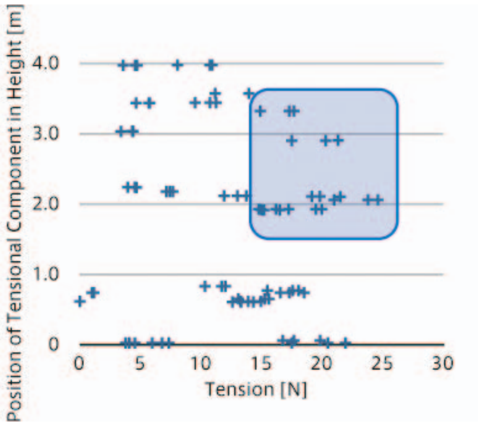


Fig. 9. Distribution of tensional force

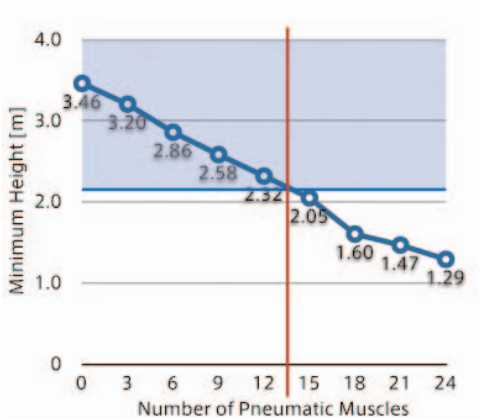


Fig. 10. Change in height of the structure

TABLE III
SIMULATION PARAMETERS

Parameters	Values
Length of strut	4000 mm
Mass of strut	0.2 kg
Natural length of cable	2140 mm
Spring constant of cable	300 N/m
Mass of cable	0 kg

cles are elongated. 12 pneumatic muscles make the minimum height 2.32 m which is safe for an ordinary adult not to touch or hang on components as shown in Fig. 10.

Using these conditions dynamical simulation was performed. Fig. 11 shows the screen captures of dynamical simulation. Fig. 11(a) represents a state where all pneumatic muscles are elongated and Fig. 11(b) contracted. In Fig. 11, colored lines represent pneumatic muscles; blue ones are elongated and red ones are contracted. Table III shows simulation parameters.

IV. ARCHI/E MACHINA

In this section, the detail information of the prototype of interactive architectural-space is described. The design of the prototype is based on the method stated in section III. This prototype is named "Archi/e Machina". Table IV shows all

TABLE IV
ARCHI/E MACHINA'S PARAMETERS

Structural Parameters	Values
Number of Struts	21
Number of Cables	84
Number of Nodes	42
Cables per Nodes	4
Strut's Length per Cable's Length	1.852
Material of Strut	Aluminum
Length of Strut	4000 mm
Mass of Strut	0.4 kg
Material of Cable	Steel Wire
Length of Cable	2140 mm
Mass of Cable	0.1 kg
Total Weight	18 kg
Moving Parameters	**Values**
Generative Force Needed	25 N
Number of Pneumatic Muscle	12
Natural Length of Pneumatic Muscle	2410 mm
Mass of Pneumatic Muscle	0.05 kg
Maximum Height of Structure	3460 mm
Minimum Height of Structure	2320 mm

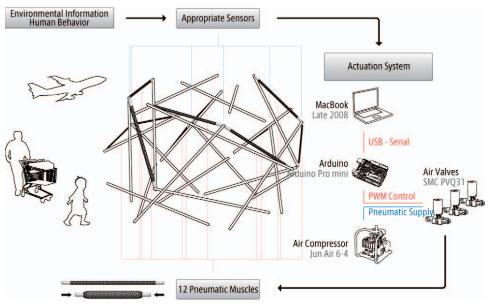


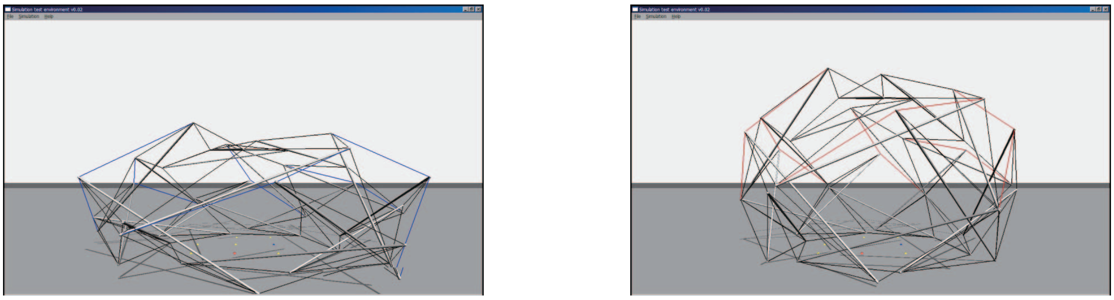
Fig. 12. System overview of Archi/e Machina

parameters concerned with designing and constructing Archi/e Machina.

Fig. 12 shows the system overview of Archi/e Machina. Environmental information such as human behavior and environmental parameters are sensed and analyzed by appropriate sensors and PCs. Then each pneumatic muscles is controlled independently by pneumatic valves using micro-controllers and electric circuit. The pneumatic valve can control the direction and the speed of airflow so that the whole space can move very complexly according to environmental information.

A. *Half-scale Prototype*

Firstly, a half-scale prototype was made. Fig. 13 shows the half-scale model of Archi/e Machina. This model was exhibited at Haneda Airport in Tokyo as one of artworks in "Air Harbor - Digital Public Art Exhibitoin". People could not enter the space because of its scale so that the acoustic information in the airport or by people was used as the "Environmental information" in Fig. 12. People enjoyed seeing that Archi/e Machina reacted to the announcement of air port and interacting



(a) Collapsing State (No muscles contract)

(b) Rising State (12 muscles contract)

Fig. 11. Simulation of dynamic movement

Fig. 13. Archi/e Machina (Half Scale)

Fig. 14. Archi/e Machina (Full Scale)

with clapping, jumping and speaking.

B. *Full-scale Prototype*

Based on the succeed of making half-scale model, full-scale model of Archi/e Machina was actualized as shown in Fig. 14. Full-scale model has the same parameters as described in Table IV and uses Infra-red sensors to detect human movement inside itself. People can enter and move around the space that react to their behavior. Fig. 15 shows the example of the movement of Archi/e Machina.

As shown in this section, "Archi/e Machina", a new prototype for interactive architectural-space that can interact with inhabitants by moving its whole space, was successfully realized.

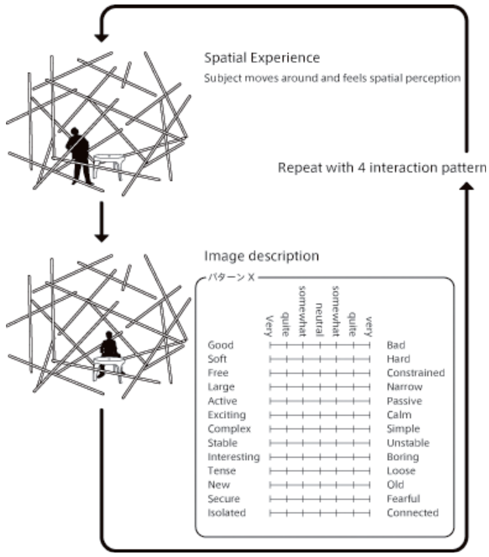


Fig. 16. Scheme of experiment

V. Experiments and Results

In this section, the prototype "Archi/e Machina" is evaluatee with the methods of environmental psychology.

A. *Psychological Experiment*

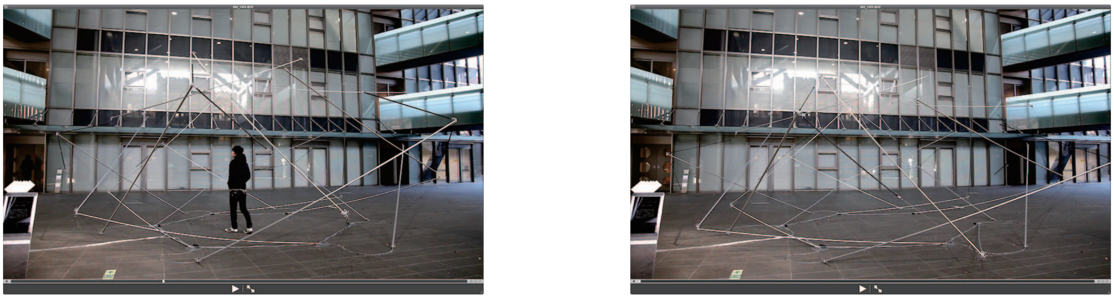
Semantic Differential Method (SDM), which was generally used in environmental psychology was applied. SDM evaluates stimuli with multiple adjective couples to illuminate psychological images. In SDM, factor analysis is used for analyzing data described by subjects.

Fig. 16 shows the scheme of the experiment and adjective couples. There are 4 patterns in interactive spatial experiences as is explained FIg. 17. This experiment was performed with 13 subjects.

B. *Results and Discussion*

Fig. 18 shows the results of the image evaluation experiment, representing the changes of factors' score of evaluation depend on interaction patterns. Principal factor analysis gave two evaluating factors interpreted as below:

- "Rest" for "Boring", "Passive", "Stable", "Old", "Simple" and "Calm"



(a) Interacting with human inside

(b) Static state

Fig. 15. Full-scale Archi/e Machina

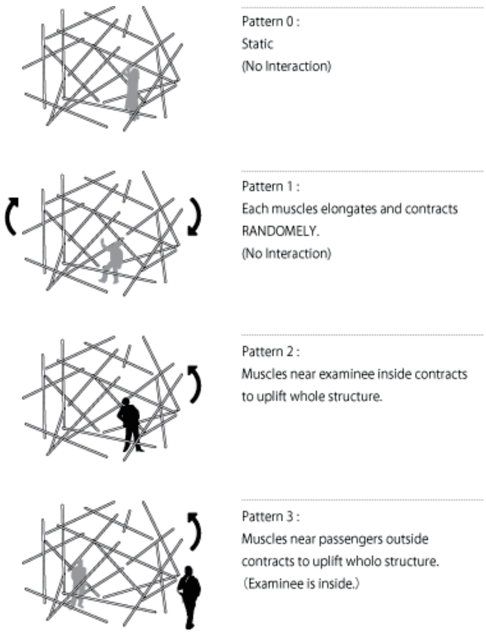


Fig. 17. Interaction pattern in experiment

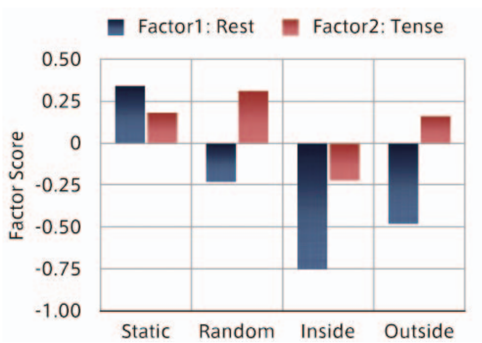


Fig. 18. Interaction pattern in experiment

- "Tense" for "Constrained", "Narrow", "Hard", "Bad", "Fearful" and "Tense"

Fig. 18 indicates that, depend on interaction patterns, the scores of two factors are radically change and spatial perception of subjects and spatial nature of Archi/e Machina trasforme.

1) "Rest" Factor: Firstly, all patterns except for pattern 0 resulted in negative "Rest" factor. This result must be because of the movement of spatial structure itself. Secondly, "Rest" factor in pattern 2 resulted in quite negative value. It seems natural because pattern 2 is the only pattern in which Archi/e Machina moves in reaction with subjects and subjects were asked to move around to feel spatial nature.

2) "Tense" Factor: "Tense" factor in patter 2 has comparatively lower value than in pattern 0 and 1, implying that synchronized movement of surrounding architectural-space decreases negative images such as "constrained", "narrow" and "fearful". This synchronization may give subjectives with active comfortability. Comparing pattern 2 and 3, pattern 3 has more unfavorable "Tense" factor. The reason may be that the control of surrounding architectural-space is apart from the subject and is determined by the accidental behavior of external passengers. This presumption leads to a hypothesis that surrounding architectural-space that moves interactively and synchronously can be felt as an augmentation of personal space so called in psychology[12].

VI. Conclusion

A. Summery of This Paper

This paper introduced increasing researches on interactive architectural-space and elucidated the importance of influence on spatial perception and spatial nature by interaction between human and architectural-space. A prototype of interactive architectural-space was made to investigate the influence. The prototype adopted tensegrity for the structure of the prototype. The image evaluation experiment indicated that surrounding architectural-space that moves interactively and synchronously can be felt as an augmentation of personal space.

B. Future Work

1) Evaluation Method: The evaluation of spatial perception in this paper may be inadequate. It has to be scrutinized how subject's personal space change according to parameters such as interaction patterns , speed of actuation, etc. If surrounding architectural-space was a kind of personal space, it would be possible to experiment the psychological influence by the contiguity to the space by other people and by external environments.

To compare these interactive architectural-space with existing robotics-based interactive room is also important.

In this paper, experiment used SDM that is generally used for evaluating existing architectural-space. However, when architectural-space itself moves, environmental parameters change drastically. To evaluate interactive architectural-space precisely, we have to establish a new evaluation method that include a point of temporal transformation of architectural-space.

2) Prototype: The prototype in this paper is just a structure and is not physically isolated with external environment. It is obvious that this structural space is not appropriate to real living environment. A prototype involved with a membrane has to be made and evaluated with more ordinary human activities.

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