An Evaluation Method for Smart Variable Space in Living Space

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Abstract. The methods which improve space usage efficiency is important especially for city lives. Development of high-rise buildings and underground is one of the methods. However, those developments just lay out the spaces which are expanded in plane into vertical. Physical and monetary limitations are the problem. Therefore, the spaces which can change its functions easily/automatically depending on the situations are necessary instead of stacking of single function spaces. So far, we have proposed Smart Variable Space which realizes various functional spaces by changing its Spatial Configuration Modules dynamically. In this research, the simulated environment for Smart Variable Space was developed by using Virtual Robot Experimentation Platform. In order to clarify the efficacy of Smart Variable Space, a new evaluation index was proposed, and then, the efficacy of Smart Variable Space in living space was assessed by comparison with the conventional housing models.

Keywords: Smart Variable Space, Intelligent Space, Architectural Furniture, Skelton Infill.

1 Introduction

Big cities, like Tokyo, have been attracting many people since olden days. The trend is no changes, and population inflow into the big cities is continuing, even Japan is going into depopulating society [1]. Cities, where various functions are concentrated in limited area, have been suffering from chronic space shortage. Therefore, high-rise buildings and underground have been developed to increase space usage efficiency. However, those developments just lay out the spaces which are expanded in plane into vertical. They require a lot of resources, high construction cost, long vertical movement, and spoil a view. Therefore, instead of stacking of single function spaces, another method is necessary to increase space usage efficiency.

We have proposed Smart Variable Space (SVS) which realizes various functional spaces by changing its Spatial Configuration Modules dynamically [2, 3]. Each module can automatically transform from wall/box into a functional space, such as, bedroom, office, according to the user's daily living cycle. So far, a bedroom type

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module (Figure.1) was developed as an example of the spatial configuration module. However, the efficacy of daily changes of living space is not verified. Even in the field of architecture, it remains in subjective evaluation by the users. In this paper, we proposed new index to clarify the efficiency of SVS and evaluate its effectiveness in living space by using the simulator. Section 2 explains related researches, section 3 explains evaluation index for SVS and section 4 describes housing and special configuration modules model in the simulator. Section 5 explains experimental method and results of the simulation. Finally, section 6 offers conclusions.

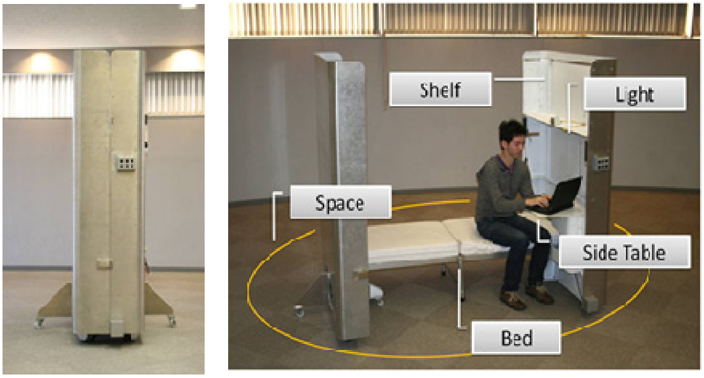


Fig. 1. Appearances of bedroom module for smart variable space

2 Related Research

2.1 Skeleton Infill

Recently, a concept of a method called skeleton-infill to extend building duration has received attention. This is the method to enhance architectural sustainability by dividing a building into two factors: the skeleton (an empty space without partitions and equipment) and infill (changeable equipment and partitions). Building duration is generally decided not on physical duration of structural skeleton but on when it cannot respond to its residents' changes of family structure or life style. In fact, duration of an architecture would be longer if it can be adaptable to such changes. The concept of the skeleton-infill which enables equipment having shorter duration than a building to be more renewable and inner room arrangement to be more changeable to respond to changes in lives has been widely accepted from the above point of view. However, infill which can change room arrangement is not easy to carry out and does not usually provide for enough changeability to respond to daily alternation of application thereof. Upon such problem consciousness, some case examples trying to solve those problems with "furniture combining architectural functions" which is like an intermediate between furniture and partitions or equipment have been carried out in order to deliver interior design of higher changeability [4-7].

2.2 Architectural Furniture

In the above-mentioned, Infill is not provided with quick-response changeability against everyday application alteration, since it is supposed to be altered in a time-span of around 15 to 30 years. Reflecting such situation, "furniture combining architectural functions" to play an intermediate role between infill and furniture have appeared.

For example, Baumhaus, Nobuaki Furuya and Studio NASCA proposed a mechanism, as a trial to enhance sustainability of rented apartments which are expected to respond to various life styles, wherein architectural part is to be an empty space without partition like a skeleton, and interior provides furniture functioning as partition as well as closet which residents can arrange interior layout by deciding how the furniture is placed [4].

Suzuki named such concept like an intermediate between infill and furniture as "furniture combining architectural functions - Architectural Furniture". Further, Architectural Furniture is defined as "what is able to segment space, provide functions in place, and to be moved and altered easily" [6, 7].

Figure.2 shows the examples of architectural furniture, mobile kitchen, foldaway guest room and foldaway office, designed by Suzuki. Each architectural furniture has casters to realize easy operation by humans. When those are folded in, its appearances look like suits case. When those are folded out, kitchen space, guest room, and study room appears. However, one or two operators are required due to the size and weight.

Fig. 2. Folding in and out of three types of Architectural Furniture

2.3 Robotized Structurization of Living Environment

On the other hand, there are many researches which apply information and robot technology into living environment to give intelligence and achieve various services. For example, Sato developed robotic room which supports daily activities of bedridden patients/student living alone in the room, using embedded sensors in furniture and robot arm [8]. Hashimoto proposed intelligent space and developed DIND (distributed intelligent network device) which had various sensors and communication device, and then studied the navigation of robots, wheelchair and people with visually impairment [9]. Ohara studied ubiquitous robot system which provides physical services by cooperation with distributed robot functions in environment [10]. Sugano developed WABOT-HOUSE. Robotic partition and movable kitchen were installed in the house to realize daily changes in a layout to meet various life styles of the residents. Automatic change of the layout and cooperative movement with mobile robot were achieved using sensors and RFID in the environment [11]. Tanikawa developed active caster with a built-in motor to physically assist people with disabilities. The object (table, chair, door, etc.) to be moved can be maneuvered easily and remotely by the casters attached to it [12]. However, the research which focused on efficiency improvement of the space is rare.

2.4 Smart Variable Space

Architectural furniture is suitable for the change in a layout that is more daily than Skeleton Infill. Additionally, the character of architectural furniture is effective for the efficiency improvement of the space. Even narrow space could have various functions by preparing various architectural furniture modules. However, architectural furniture requires one or two operators due to the size and weight. Against this problem, robot technology can offer a solution; even more can add some intelligence and autonomy. Smart Variable Space is the expanded concept of architectural furniture by combining with robot technology. The space is composed with robotic architectural furniture, such as bedroom, and office room, and can change its functions automatically according to the users demand or lifestyles.

3 Evaluation Index for SVS

Present floor plan of house is divided into living, kitchen, study, bedroom, and etc. according to the function. The resident moves the room according to the usage. At this moment, the room not used is a useless space in the viewpoint of the space efficiency improvement. Therefore, we introduce a concept of "available area; A_{avail}". A_{avail} is defined as the area excluding disused area from the evaluating area, $A_{eval.}$ A_{avail} changes according to the user's daily living activities. The each activity is expected to continue some period of time. So, we defined "available area rate; P_i" as follows;

$$P_i = \frac{A_{avail.i}}{A_{eval}} \tag{1}$$

Here, $A_{avail,i}$ is A_{avail} in the i^{th} time period. On the other hand, the time for changing spatial functions, $T_{trs.j}$, is much smaller than time for a user's daily living activity. $T_{trs.j}$ is j^{th} time period for changing space function; means the time for transposing of spatial configuration modules in SVS, and moving to other rooms in conventional housing. We defined "available area in transposing; $A_{trs.j}$", and the rate; $P_{trs.j}$ as follows;

$$P_{trs.j} = \frac{A_{trs.j}}{Aeval} \tag{2}$$

Then, the total average available area; P_{avg}, was defined as follows;

$$P_{avg} = \alpha \frac{\sum_{i=1}^{N} P_i T_i}{T_{all} - \sum_{j=1}^{M} T_{trs.j}} + \beta \frac{\sum_{j=1}^{M} P_{trs.j} T_{trs.j}}{\sum_{j=1}^{M} T_{trs.j}} \tag{3}$$

Here, α and β are weight parameters. Finally, we explain "evaluating area; A_{eval}". A_{eval} is defined as the area excluding plumbing equipments/product area and storage area from total internal dimension of the housing; because, those are difficult to rearrange or not necessary to change its function. Figure.3 shows the relationship between the available area rates and the time periods.

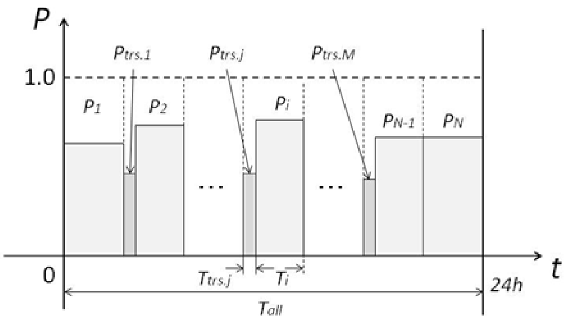


Fig. 3. Relationship between available area rate and time period

4 Simulator

In order to evaluate SVS in various situations, we made housing and spatial configuration module models by using the simulator, named V-REP [13]. We use this simulator to visualize the space and to obtain the information on the movements.

4.1 Housing models

SVS assumes big city, therefore, apartment is the target housing. The SVS housing model was made as a studio apartment which internal dimension was 50 square meter. The dimension came from "compact mansion", a new category of apartment, for singles and couples in Japan. Figure.4 shows its room arrangement. Plumbing products/equipments, such as toilet and bathroom were arranged in one side to create large working space for spatial configuration modules. On the other hand, a conventional housing model was made for comparison (Figure.5). The model was "nLDK" apartment which had been provided by the public corporation, and became the common arrangement of present apartment in Japan. The internal dimension was defined as 70 square meter which was average dimension in Tokyo area.

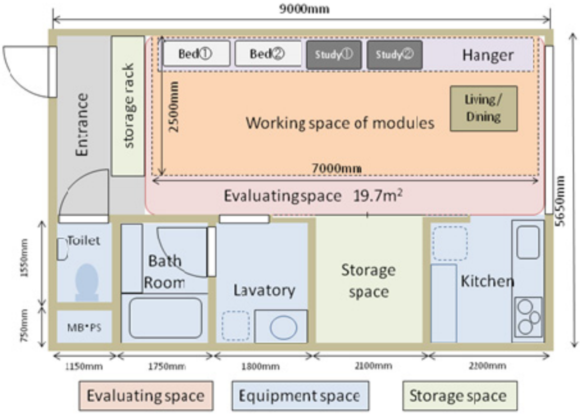


Fig. 4. Room arrangement of SVS housing model

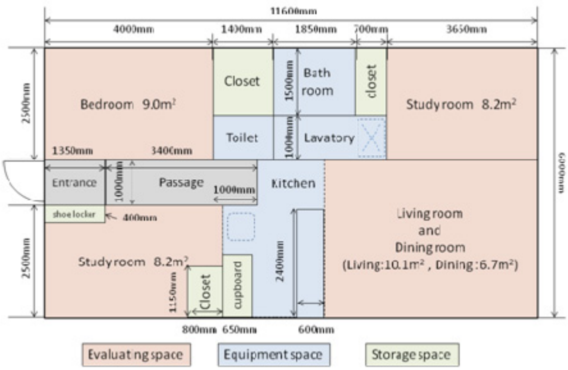


Fig. 5. Room arrangement of conventional housing model

4.2 Models of Spatial Configuration Module

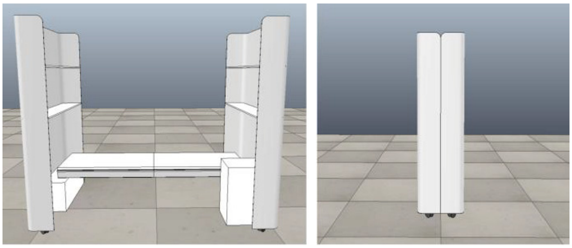
From the view point of housing studies, we extracted the major spatial functions from the relationship between activities of daily living and kind of rooms. As the results, the functions were "bedroom", "study room", "living room", and "dining room". We made the spatial configuration module virtual models which had these functions in the V-REP. These module models have autonomy.

Bedroom and study room module are single function type module. These modules have two modes, fold out and fold in. Bedroom module model is designed based on real bedroom module developed in previous research. Four omnidirectional wheel models are installed as the moving mechanism. And imaginary torque is applied to fold in/out at the each joint. The working speed of the module is also decided according to the real bedroom module. This speed is commonly used in other two module models because they are not realized in actual modules. Figure.6 and Table 1 show its appearance and specifications.

As for the study room module model, the appearance and dimensions are decided based on office room type architectural furniture. The moving mechanism is same as the bedroom module model. The study room module folds in/out like a large book. Figure.7 and Table 2 show its appearance and specifications.

As for the living and dining room, the module model is designed to have those two functions in one module because those are exclusively used in daily activities. The module has three modes, living room, dining room and fold in. the module assumes to have omnidirectional wheels as moving mechanism. Imaginary torque is applied at each joint for transformation. The details of deformation mechanics will be presented in the future. Figure.8 and Table 3 shows its appearance and specifications.

In this research, we didn't consider weight of all module models in order to focus on changing arrangement of the modules.

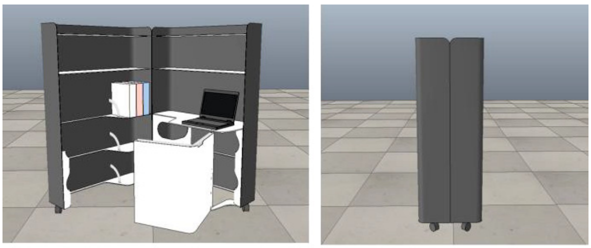


(a) Fold out (b) Fold in

Fig. 6. Appearance of bedroom module model

Table 1. Specification of bedroom module model

	Fold out	Fold in
Width	2040 [mm]	440 [mm]
Depth	1200 [mm]	
Height	1770 [mm]	
Occupation Area	2.45 [m²]	0.53 [m²]
Moving speed	–	0.4 [km/h]
Swing speed	–	7.5 [deg/sec]



(a) Fold out (b) Fold in

Fig. 7. Appearance of study room module model

Table 2. Specification of study room module model

	Fold out	Fold in
Width	1281 [mm]	520 [mm]
Depth	1261 [mm]	1000 [mm]
Height	1518 [mm]	
Occupation Area	1.62 [m^2]	0.52 [m^2]
Moving speed	—	0.4 [km/h]
Swing sped	—	7.5 [deg/sec]

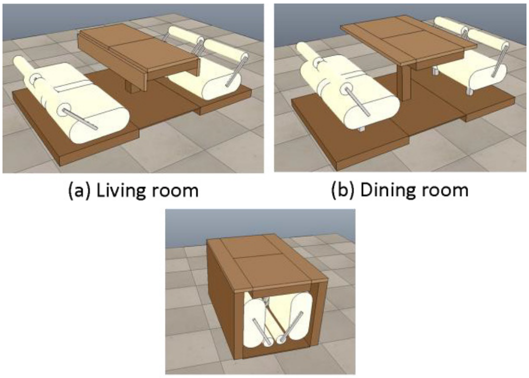


Fig. 8. Appearance of living-dining room module model

Table 3. Specification of living-dining room module model

	Living	Dining	Fold in
Width	1960 [mm]	1960 [mm]	800 [mm]
Depth	1200 [mm]	1200 [mm]	1200 [mm]
Height	780 [mm]	580 [mm]	780 [mm]
Occupation Area	2.35 [m^2]	2.35 [m^2]	0.96 [m^2]
Moving speed	—	—	0.4 [km/h]
Swing speed	—	—	7.5 [deg/sec]

4.3 Resident Model

In the conventional housing model, time for changing spatial functions corresponds to the resident's walking time from room to room. Moreover, how change the spatial functions depends on the household composition and resident's lifestyle. In this research, we targeted couple household increasing the number recently [14]. A young couple model was made based on the average physical data of Japanese male and female (Table 4) [15]. Meanwhile, their day-to-day timetable was defined using the statistical data published by the Ministry of Internal Affairs and Communications, Japan [16]. The timetable was divided into 48 time periods, and then, we extracted the rooms as spatial functions which corresponded to their activities of daily living at each time period (Table 5).

Table 4. Specification of residents model

Sex	Male	Female
Age	25 - 34	25 - 34
Average height [cm]	172.1	158.7
Walking speed [m/s]	1.5	1.21

Table 5. Day-to-day timetable of the residents

<table>
<tr><th rowspan="2">Time</th><th colspan="2">Room</th><th rowspan="2">Scene</th></tr>
<tr><th>Male</th><th>Female</th></tr>
<tr><td>0:00
|
6:00</td><td>Bedroom</td><td>Bedroom</td><td>Scene 1</td></tr>
<tr><td>6:30</td><td>Lavatory</td><td>Kitchen</td><td rowspan="7">Scene 2</td></tr>
<tr><td>7:00</td><td>Dining room</td><td>Dining room</td></tr>
<tr><td>7:30</td><td rowspan="4">Go to work</td><td>Kitchen</td></tr>
<tr><td>8:00
|
18:00</td><td>Go to work</td></tr>
<tr><td>18:30</td><td rowspan="2">Kitchen</td></tr>
<tr><td>19:00</td></tr>
<tr><td>19:30</td><td>Dining room</td><td>Dining room</td></tr>
<tr><td>20:00</td><td rowspan="2">Living room</td><td>Kitchen</td><td rowspan="5">Scene 3</td></tr>
<tr><td>20:30</td><td rowspan="4">Living room</td></tr>
<tr><td>21:00</td><td>Bath room</td></tr>
<tr><td>21:30</td><td rowspan="2">Living room</td></tr>
<tr><td>22:00</td></tr>
<tr><td>22:30</td><td rowspan="3">Study room</td><td>Study room</td><td rowspan="3">Scene 4</td></tr>
<tr><td>23:00</td><td>Bath room</td></tr>
<tr><td>23:30</td><td>Study room</td></tr>
</table>

5 Experiment

5.1 Methods

Switching points of spatial functions were extracted from the timetable. 4 scenes, bedroom scene (Scene 1; 0:00-6:30), dining room scene (Scene 2; 6:30-20:00), living room scene (Scene 3; 20:00-22:30), study room scene (Scene 4; 22:30-0:00) were defined. In order to have same spatial functions in conventional housing model, two bedroom and study room modules, and one living-dining module were installed in the housing model for SVS. The layout of the modules in each scene are shown in Figure.9. We defined minimum path for each modules and residents models to change the scenes, and then, simulated their movement at each switching points of the scenes. The paths of residents models are described in Figure 10. The blue and red line means male's and female's path, respectively.

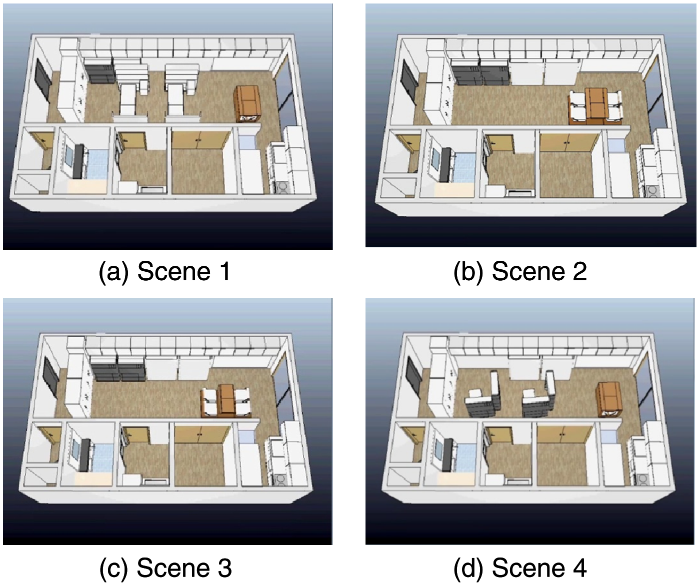


Fig. 9. Layout of the modules in each scene

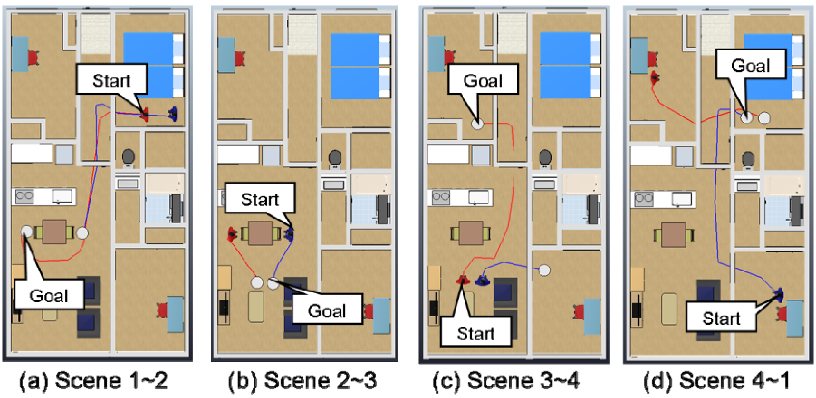


Fig. 10. Walking paths of resident model

5.2 Results

A_{eval} of each housing model were measured as 19.7 m^2 in SVS housing, and 42.2 m^2 in conventional housing. The results of required times for changing spatial functions in each housing model are described in Table 6. SVS required longer time in every switching point. The maximum required time was 70 sec. at the switching point from the scene 4 to 1. Then, the total average available area, P_{avg} was calculated by equation (3). In this research, weight parameters, α and β, were defined as follows:

$$\alpha = \frac{T_{all} - \sum_{j=1}^{M} T_{trs.j}}{T_{all}} \tag{4}$$

$$\beta = \frac{\sum_{j=1}^{M} T_{trs.j}}{T_{all}} \tag{5}$$

As for the conventional housing model, all of the evaluating area is not used during the residents walking from the room to room. Therefore, the value of equation 2 is always zero. Besides, the time for changing spatial functions, $T_{trs.j}$ was defined to use smaller one among the residents. Table 7 shows the results of both housing models. SVS housing required longer time for changing spatial functions in comparison with conventional housing. However, the time, 187 sec. is much smaller than 24 hours. On the other hand, SVS housing's P_{avg} is about 4 times higher than the value of conventional housing.

Table 6. Required times for changing spatial functions

	SVS [sec]	Male [sec]	Female [sec]
Scene 1-2	62.00	4.10	7.65
Scene 2-3	6.00	1.65	1.80
Scene 3-4	49.00	1.85	5.75
Scene 4-1	70.00	6.20	4.45

Table 7. Results of total avarage available area

	Conventional housing	SVS housing
P_{avg}	0.24	0.96
$\sum_{j=1}^{M} T_{trs.j}$	12 [sec]	187 [sec]

6 Conclusion

In this paper, we proposed an evaluation index for variable space which changes its spatial functions in daily. The new concept, "available area rate: P_i" and "available area rate in transposing: $P_{trs.j}$" were introduced to evaluate the space use efficiency in every time period. SVS and conventional housing model, and young couple household model were made, and then the efficacy of SVS was evaluated using simulator. The result showed SVS housing have high space use efficiency. In order to investigate more suitable target and necessary modules for SVS, we will further experiment to evaluate the efficacy in various housing, households, and lifestyle model.

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