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BIO-MIMETIC ARTICULATED MOBILE ROBOT OVERCOMING STAIRS BY USING A SLINKY MOVING MECHANISM

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ABSTRACT

Bio-mimetic articulated robots are robots that imitate living creatures and have many modules. There are many kinds of robots and they are used for many purposes but we decided that the most important one is overcoming obstacles, especially stairs. In this paper, we used axiomatic design theory to improve these kinds of robots and finally decided one complete design – a "slinky" robot. We find that the prototype of a slinky robot has many advantages for overcoming stairs compare to other types of robots. Finally, we discuss the limitations of the prototype and potential solutions to those problems.

Keywords: Bio-mimetic, Slinky, Robot, Stairs, Axiomatic Design

1 INTRODUCTION

Biomimetics is the word most frequently used in scientific and engineering literature that is meant to indicate the process of understanding and applying (to human designs) biological principles that underlie the function of biological entities at all levels of organization. Among the many fields of study of Bio-Mimetic, one area is the Mobile Robot. There are many issues in this research. The first one is overcoming obstacles safely and adapting to rough terrain. This is the main subject in our project, so we are focused on this. The second one is finding proper robot structures for these kinds of functions. This means we should make the robot have stable, precise and elaborate movement. Meanwhile in this area, many bio-mimetic robots such as centipedes, snakes, dogs, birds and even humans exist now. These robots are used by the military, industry, medical service, transportation, exploration industry and the home-related industry. Presently these are prominent in the military and scout field because they can probe rough, narrow, dangerous or unknown places where it is too dangerous or hostile and people cannot go. Therefore, since those robots can do missions instead of people, it is important to develop them.

In this paper, we will first explain past research related to our problems and show our customer needs derived from expert interviews. Next, we suggested three alternative design concepts to solve our problem and selected one which was the best. After that we decided the functional requirements and design parameters. We also repeated the process of developing our final concept: the robot derived from a "slinky" spring toy.

2 BACKGROUND RESEARCH

2.1 LITERATURE SEARCH

Scientists have tried to imitate characteristics of living things for many years. In order to produce the robot which has the same ability of living things, they imitated several animals or insects such as snakes, scorpions and centipedes [1, 4]. Therefore, those robots can be separated by types of moving method such as track type, wheel type, jumping type and so on.

Specifically, many robots which have many modules or articulations like centipedes or snakes have been researched a lot because attaching many modules is more advantageous for overcoming obstacles than any other forms [2-3]. Many scientists suggested several methods of movement which are advantageous for overcoming obstacles and tried to make them [2-3].

2.2 RESULT OF CUSTOMER INTERVIEWS

We interviewed people who work for Robolink and researchers in KAIST Mechanical Engineering labs (using cell phone or visiting). First, we asked about the kinds of work that the robot related to our project can do. According to them, overcoming obstacles, probing into dangerous places, and rescuing people in dangerous places are the main functions. However, the most basic function is overcoming obstacles to probe or rescue.

Second, the researchers we interviewed gave us advice for what kinds of functions are needed these days. The first one was the function to overcome obstacles, especially stairs which are the most difficult obstacles for robots. The second one was the function for self-position recognition. They said that if only one of two is possible, our design would be successful. They wanted us to think of a new moving mechanism for overcoming the stairs.

2.3 FINAL CUSTOMER NEEDS

Our experts emphasized that the most important function in a bio-mimetic articulated mobile robot is overcoming obstacles (especially stairs) and moving flexibly. Also, they said the robot needs to be durable and strong, and if possible to reduce expenses. You can find our customer needs in figure 1.

2.3.1 Technical Aspect	
(1) New moving mechanism	- Be simple, accurate and stable. - Move in many directions - Move to various heights
(2) Ability to overcome obstacles	- Strong, flexible and well-balanced structure - Overcome stairs
(3) Durability	- Structure can endure the impact from external environment
2.3.2 Financial Aspect	
(1) Reducing expenses	- Use inexpensive materials - Reduce its components and useless functions

Figure 1. Customer Needs

3 DESIGN SOLUTION

3.1 ALTERNATIVE DESIGN CONCEPTS

After deriving our customer needs, we developed three basic concepts to achieve our goals. Concept 1 is a grasshopper robot which jumps to overcome obstacles. Concept 2 is a snake robot which rolls on the ground and climbs up the stairs using two end absorbers. Concept 3 is a spring robot which also climbs up the stairs moving the center of gravity like the slinky which has a unique movement (figure 2).

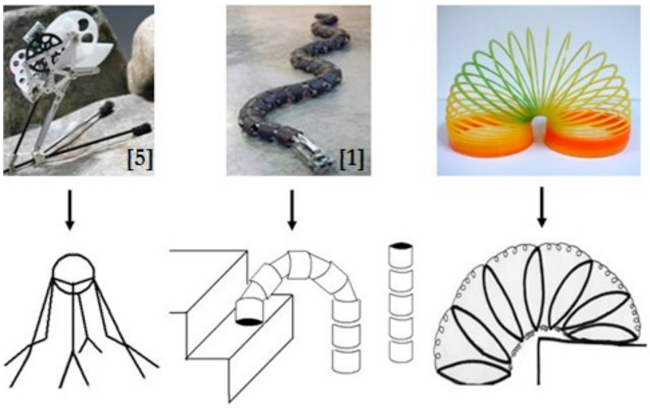


Figure 2. Three Design Concepts

3.1.1 ALTERNATIVE DESIGN CONCEPTS

The first task was to plan the robot which satisfies the primary CNs (Customer Needs): Technical Aspects. Specifically, the new moving mechanism and ability to overcome obstacles was the first consideration when designing the robot. Therefore, we considered two points: what can we imitate to overcome various obstacles and how can we be creative? Concept 1 and 2 were designed by the method which mixes past robots that have advantageous functions for overcoming obstacles with a new one.

Concept 1 was modeled with four grasshopper robots from past research which were small and light, and also could jump as high as 1.5meters. Attaching 4 grasshopper robots on 4 sides makes the robot move in 4 directions and overcome obstacles (figure 3). The center of gravity is on the head and this head softens the impact when this robot collides with the ground. Legs are put down to make initial form after landing (figure 4).

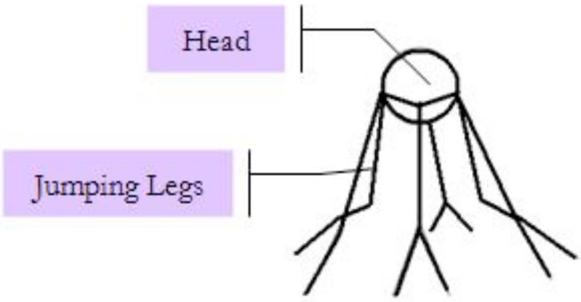


Figure 3. The appearance of concept 1

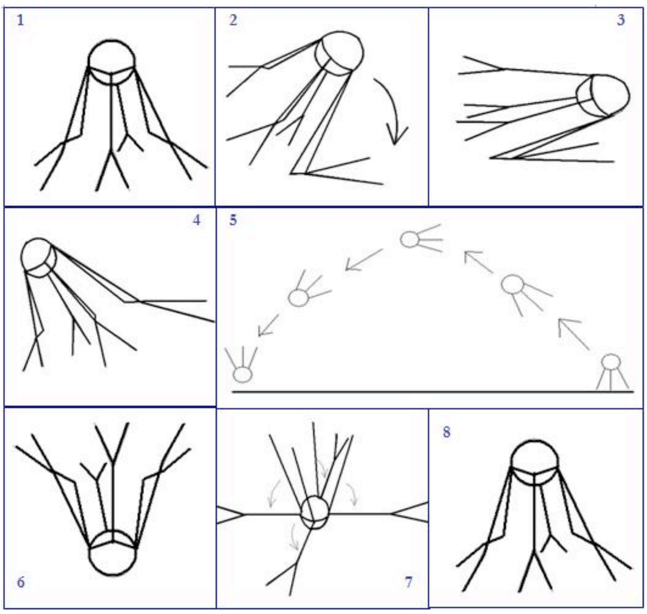


Figure 4. Moving mechanism of concept 1

Concept 2 is a remodeled robot where absorbers were added to the main body of a snake robot. The snake robot from past research is a good model which can overcome various obstacles. However, it cannot climb up the stairs by bending its body. Therefore, we solved this problem with two absorbers attached to each ends of the robot (figure 5). The absorbers were fixed its end of body to upper ground of stair and helped to lift the body (figure 6). Therefore, a snake robot, which had just rolling movement, was designed to be a new model.

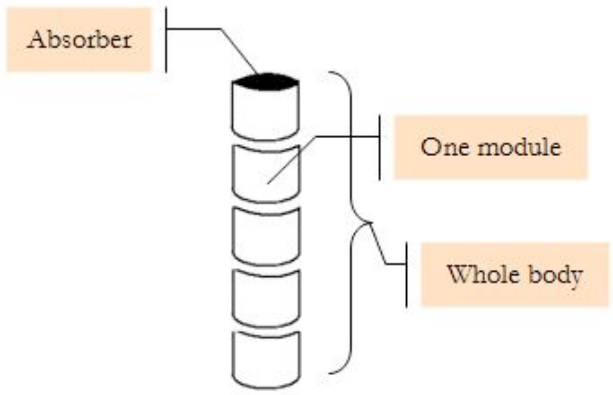


Figure 5. The appearance of concept 2

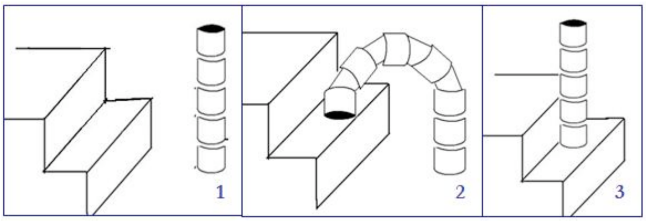


Figure 6. Moving mechanism of concept 2

Concept 3 is our own robot, which imitates the slinky toy (figure 7). Our robot has a new moving mechanism. We designed the past toy model, which could just go down moving the center of gravity, conversely to be the robot which can even climb up the stairs (figure 8). Moreover, the length of the robot can be controlled mechanically using motors and springs much like the real toy is shortened or lengthened with our own hands. As a result, it satisfies the CNs in Technical Aspect.

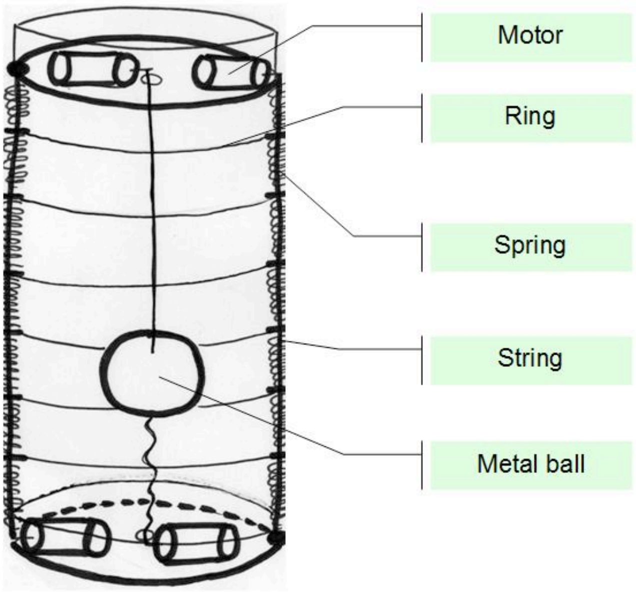


Figure 7. The appearance of concept 3

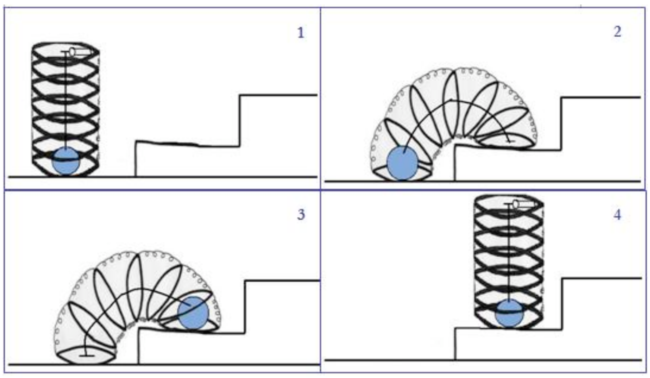
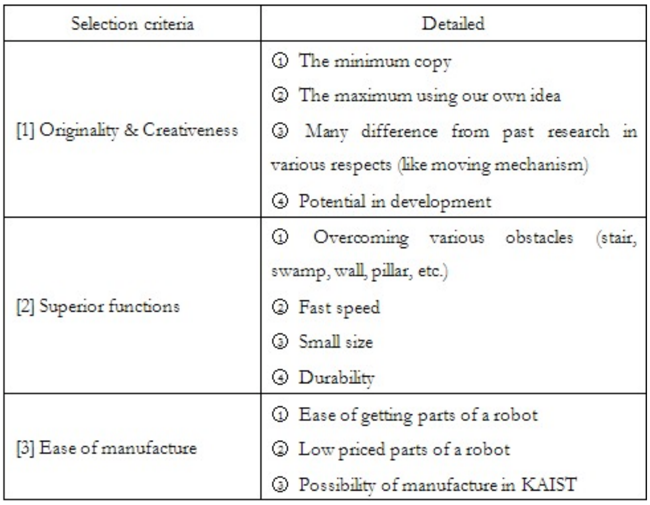


Figure 8. Moving mechanism of concept 3

All of these concepts are symmetrical and have many articulations, so they all satisfy the CNs for good balanced and a strong structure.

3.1.2 SELECTION CRITERIA

Selection criteria were used to evaluate and rate our concepts. In order to choose effective criteria, we considered the strong and weak points of our concepts and also we discussed which criteria are more important than the others. Finally, three main selection criteria and eleven detailed criteria were selected (figure 9).



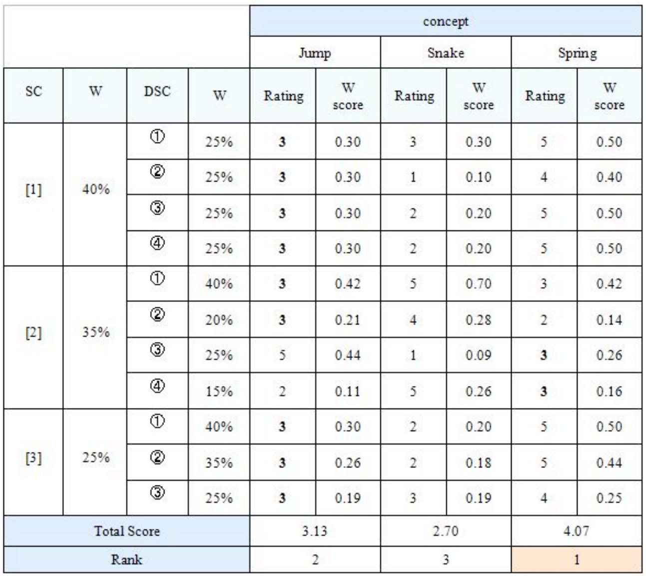
Selection criteria	Detailed
[1] Originality & Creativeness	① The minimum copy ② The maximum using our own idea ③ Many difference from past research in various respects (like moving mechanism) ④ Potential in development
[2] Superior functions	① Overcoming various obstacles (stair, swamp, wall, pillar, etc.) ② Fast speed ③ Small size ④ Durability
[3] Ease of manufacture	① Ease of getting parts of a robot ② Low priced parts of a robot ③ Possibility of manufacture in KAIST

Figure 9. Selection Criteria

First, originality & creativeness was considered as social aspects. Second, superior functions were considered as technical aspects. Finally, ease of manufacture was considered as an economic aspect.

3.1.3 CONCEPT SELECTION

In this process, we used a mixed selection method which contains external decisions, pros and cons and decision matrices. However, the main method was decision matrices.



				concept					
				Jump		Snake		Spring	
SC	W	DSC	W	Rating	W score	Rating	W score	Rating	W score
[1]	40%	①	25%	3	0.30	3	0.30	5	0.50
		②	25%	3	0.30	1	0.10	4	0.40
		③	25%	3	0.30	2	0.20	5	0.50
		④	25%	3	0.30	2	0.20	5	0.50
[2]	35%	①	40%	3	0.42	5	0.70	3	0.42
		②	20%	3	0.21	4	0.28	2	0.14
		③	25%	5	0.44	1	0.09	3	0.26
		④	15%	2	0.11	5	0.26	3	0.16
[3]	25%	①	40%	3	0.30	2	0.20	5	0.50
		②	35%	3	0.26	2	0.18	5	0.44
		③	25%	3	0.19	3	0.19	4	0.25
Total Score				3.13		2.70		4.07	
Rank				2		3		1	

Figure 10. Concept Scoring
(SC : Selection Criteria, W : Weight, DSC : Detailed Selection Criteria, W score : Weight score)

In our selection scheme, each design could receive between 1 and 5 points. Average designs received 3 points.

We gave the total 100% weight to each criterion (selection criteria and detailed selection criteria) in order to consider both weights. Therefore, we can get W scores by multiplication of 'Rating', 'W of DSC' and 'W of SC'.

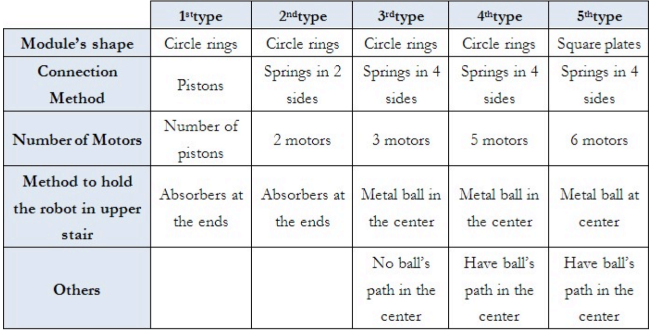
$$\text{W score} = \text{Rating} \times \text{W of DSC} \times \text{W of SC}$$

According to the result of the total score of the decision matrices, we concluded that concept 3 is the best robot to produce among these three concepts.

3.2 DESIGN DEVELOPMENT

3.2.1 CONCEPT DEVELOPMENT

The original version of the chosen concept was a snake-like robot which has absorbers at the ends. The 1st type robot has pistons for connection and absorbers producing a vacuum for the holding robot (figure 11). However, pistons are too heavy to support the bending shape of the robot. Therefore, we changed the connection method to light springs in two opposite sides of the robot so it can bend in two directions, and each side of the springs has one motor. After that, the mass of the absorbers become a problem. Those are too heavy to support the bending shape of the robot, too. Consequently, we replaced it with a heavy metal ball. By controlling the position of the metal ball, we can move the robot to the upper stair. In the final version, we used square plates because of the difficulty of making rings. We also used 6 motors, 4 motors to contract springs and 2 motors for metal ball. There is a path for the metal ball.



	1st type	2nd type	3rd type	4th type	5th type
Module's shape	Circle rings	Circle rings	Circle rings	Circle rings	Square plates
Connection Method	Pistons	Springs in 2 sides	Springs in 4 sides	Springs in 4 sides	Springs in 4 sides
Number of Motors	Number of pistons	2 motors	3 motors	5 motors	6 motors
Method to hold the robot in upper stair	Absorbers at the ends	Absorbers at the ends	Metal ball in the center	Metal ball in the center	Metal ball at center
Others			No ball's path in the center	Have ball's path in the center	Have ball's path in the center

Figure 11. Evolution of Concept 3 Development (earlier version from left)

3.2.2 FRS AND DPS

The introductions of our main functional requirements are below. You can find the details of our FRs, DPs, and design matrix in figure 12 and figure 13.

FR1. Overcome stairs

This functional requirement is the final object of our design. Our customer needs require robots that can overcome various heights. So we are basically required to overcome stairs.

FR2. Move fluently

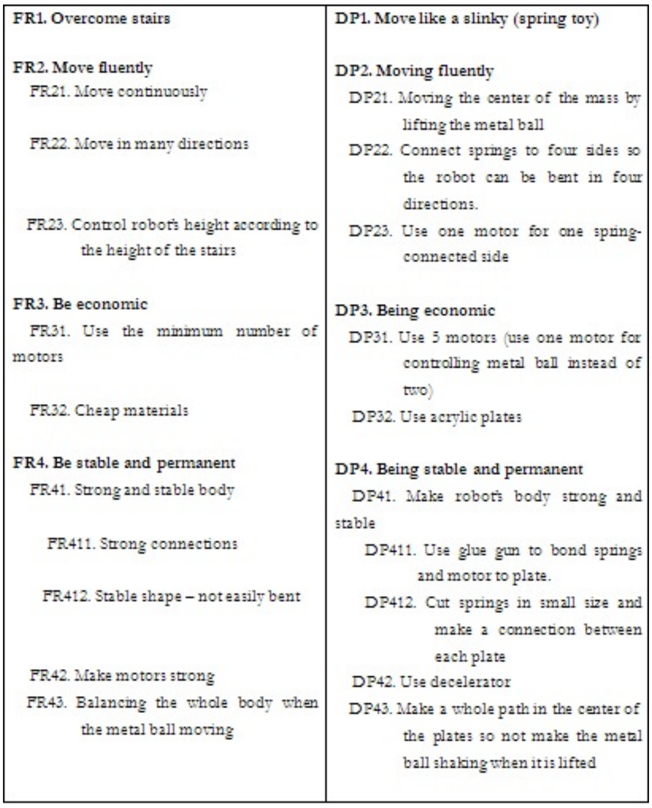
To overcome stairs, the following three sub Functional Requirements are important. Basically, the robot is required to move continuously because stairs are continuous. Also, it should move in four directions. The most critical function is that the robot is strongly required to control its body's height according to the stairs' design. This function is a very advanced function compared to other stair-overcoming robots.

FR3. Be economic

Reducing prime cost is very important in the market because by reducing prime cost, we can expect the highest profit. Therefore, the robot is required to be economical.

FR4. Be stable and permanent

If the robot wants to do its missions, it should be stable and permanent. In our case, the robot is required to be a shock-resistant robot. This means it should have strong connections. Also, the robot needs a stable state when it stands straight.



FR1. Overcome stairs	**DP1. Move like a slinky (spring toy)**
FR2. Move fluently	**DP2. Moving fluently**
FR21. Move continuously	DP21. Moving the center of the mass by lifting the metal ball
FR22. Move in many directions	DP22. Connect springs to four sides so the robot can be bent in four directions.
FR23. Control robot's height according to the height of the stairs	DP23. Use one motor for one spring-connected side
FR3. Be economic	**DP3. Being economic**
FR31. Use the minimum number of motors	DP31. Use 5 motors (use one motor for controlling metal ball instead of two)
FR32. Cheap materials	DP32. Use acrylic plates
FR4. Be stable and permanent	**DP4. Being stable and permanent**
FR41. Strong and stable body	DP41. Make robot's body strong and stable
FR411. Strong connections	DP411. Use glue gun to bond springs and motor to plate.
FR412. Stable shape – not easily bent	DP412. Cut springs in small size and make a connection between each plate
FR42. Make motors strong	DP42. Use decelerator
FR43. Balancing the whole body when the metal ball moving	DP43. Make a whole path in the center of the plates so not make the metal ball shaking when it is lifted

Figure 12. FRs and DPs for Concept 3

Following the traditional axiomatic design matrices, large x(X) means coupling and zero (O) means no coupling.

$$\begin{pmatrix} \text{FR1} \\ \text{FR2} \\ \text{FR21} \\ \text{FR22} \\ \text{FR23} \\ \text{FR3} \\ \text{FR31} \\ \text{FR32} \\ \text{FR4} \\ \text{FR41} \\ \text{FR411} \\ \text{FR412} \\ \text{FR42} \\ \text{FR43} \end{pmatrix} = \left(\begin{array}{cccccccccccccc} X & O & O & O & O & O & O & O & O & O & O & O & O & O \\ O & X & & & & O & O & O & O & O & O & O & O & O \\ O & & X & O & O & O & O & O & O & O & O & O & O & O \\ O & & O & X & O & O & O & O & O & O & O & O & O & O \\ O & & O & O & X & O & O & O & O & O & O & O & O & O \\ O & O & O & O & O & X & & & O & O & O & O & O & O \\ O & O & O & O & O & & X & O & O & O & O & O & O & O \\ O & O & O & O & O & & O & X & O & O & O & O & O & O \\ O & O & O & O & O & O & O & O & X & & & & & \\ O & O & O & O & O & O & O & O & & X & O & O & O & O \\ O & O & O & O & O & O & O & O & & O & X & O & O & O \\ O & O & O & O & O & O & O & O & & O & O & X & O & O \\ O & O & O & O & O & O & O & O & & O & O & O & X & O \\ O & O & O & O & O & O & O & O & & O & O & O & O & X \end{array}\right) \begin{pmatrix} \text{DP1} \\ \text{DP2} \\ \text{DP21} \\ \text{DP22} \\ \text{DP23} \\ \text{DP3} \\ \text{DP31} \\ \text{DP32} \\ \text{DP4} \\ \text{DP41} \\ \text{DP411} \\ \text{DP412} \\ \text{DP42} \\ \text{DP43} \end{pmatrix}$$

Figure 13. Design Matrix for Concept 3

3.3 DESIGN SIGNIFICANCE

There have been some robots able to overcome stairs. Many of them are track-type robots. These robots have many limitations to climbing stairs. The most critical limitation is that these robots cannot adapt to the variety of stair sizes. Some of them cannot climb steep stairs and some of them cannot climb high stairs lift. Moreover, they usually climb stairs which only have a fixed size. But our new robot can be controlled into many different heights because it is articulated and has a system whereby the robot can be contracted and elongated. Therefore, our robot can overcome a variety of stairs. Also, it is very small, light and made with cheap materials compared to other kinds of stair-climbing robots.

We successfully made our prototype, but there are some challenges. First, this robot cannot travel fast on level ground or rough terrain because it is designed for climbing stairs. Second, it's very unstable when the robot elongates its springs as much as possible because of the weight of the motors attached on the upper side. The most critical problem is that this robot is too slow because it has to do many steps to climb stairs. To solve these problems, we need to add systems to make it travel on level surfaces or rough terrains such as adding wheels or rolling system like snake robot. To solve the instability of the robot, we should use a very heavy metal ball to hold the body of the robot, and also, we can contract the springs a little bit more as we start so the robot's height is lower and robot therefore becomes more stable. Additionally, we can make a robot that has shorter springs. The prototype that we made is too slow when it moves because of the above procedures and complexities. However, if we make a robot's moving mechanism more precise and make a handier remote controller, the above problems could be overcome.

4 RESULTS

The prototype has 9 nodes (figure 14), 6 motors (figure 15) and 4 sides. There is one motor for one side (figure 16) and as you can see in figure 11, prototype (5th type) has a path for the metal ball in the center of its body (figure 17).

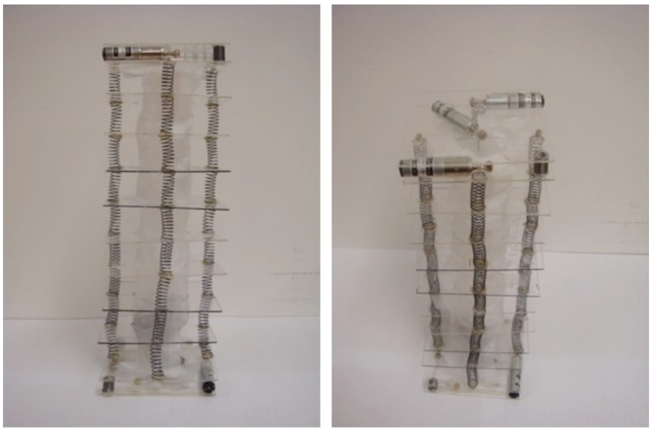


Figure 14. Prototype

Figure 15. Motors in each ends

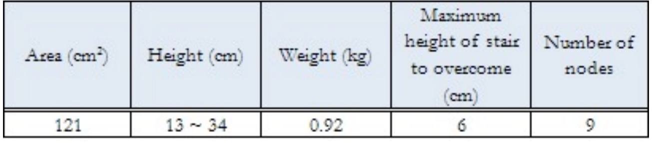
Figure 16. One motor to one spring side

Figure 17. Path of the ball

The prototype can control its body height (figure 18), so it can fix its height appropriately according to the height of stairs.

Detailed information about the prototype is shown in figure 19.

Figure 18. Minimum and maximum height of prototype



Area (cm²)	Height (cm)	Weight (kg)	Maximum height of stair to overcome (cm)	Number of nodes
121	13 ~ 34	0.92	6	9

Figure 19. Information about the prototype

Figure 20 shows how the prototype climbs stairs. First, the robot bends to the upper stairs (figure 20, picture 2). Second, it pulls up the metal ball so make the prototype be on upper stair (figure 20, picture 3). Last, it straightens its body (figure 20, picture 4).

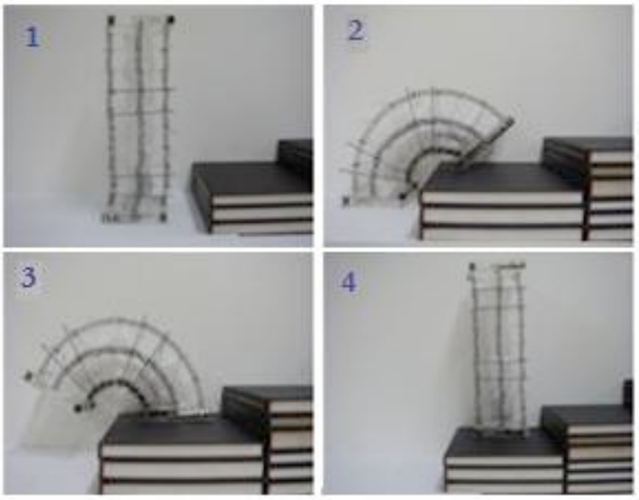


Figure 20. Overcoming stair

5 CONCLUSIONS

The fundamental goal of our project was to make an articulated robot which can overcome many constraints. The design concept is focused on overcoming stairs because customers need a robot to overcome various heights of constraints like stairs. Other researchers have designed a few robots which can overcome stairs. However, almost all of them are track-type robots so these kinds of robots have a hard time overcoming stairs with a variety of sizes.

According to the Axiomatic Design Theory, we determined functional requirements, design parameters and chose one concept among three alternative concepts. The final design concept provides all the solution of the FR. Through imitating slinky, FR1, overcoming stairs, is solved, and FR2, moving fluently, is solved by our concept's moving mechanism. FR3, being economic, is mainly solved by using cheap materials like acrylic plates. The last, FR4, being permanent and stable, is solved by a very articulated body and strong motors and connections.

The prototype has many strong advantages to overcome stairs. The most important thing is that it can overcome a variety of stair lifts (stair heights) because it is articulated – it can change its body length. This is very advanced compared with former stair-overcoming-robots, mostly track type robots. Also, the prototype is only 0.92-kg in weight, so it is much lighter and very cheap to make compared to track type robots.

Although the robot is small, light and cheap and covers various heights of stair, it has problems. It is slow because of its many procedures. In the prototype, we found that electric wires disturb the movements of the robot. To solve these problems, we have to make a robot controlled by a wireless controller. Also, we should improve the electric circuit system to shorten the interval time of movements.

6 FUTURE WORK

There are four additional issues should be considered for using in the real world – operation speed, the power/weight ratio, limit of the maximum stair height which the slinky robot can overcome and mobility.

The slinky robot needs improved operation system to increase operation speed. That operation system should have precise programs for coincidence of various operations and reducing useless operation. For instance, the operation of each motor can be programmed in a MCU (Micro Controller Unit) and the MCU should be connected to the slinky robot.

The power/weight ratio is related to the efficiency of the robot. Higher ratio causes higher efficiency and stability. To increase the power/weight ratio, the slinky robot should have a light and strong power source. If the slinky robot is fitted with light and strong motors or strong rare-earth magnets such as neodymium, it would increase the power/weight ratio.

The slinky robot needs more segmented articulations and higher flexibility of movements to increase the maximum height of stair which the slinky robot can overcome. It should have more motors or any power source in the middle of the body.

The slinky robot should operate by itself and be wireless to increase mobility. Also the robot needs to operate without human's control by utilizing MCU, MPU (Micro Processor Unit) and balancing sensors.

These kinds of works will make the slinky robot used in the real world with much more efficiency.

7 ACKOWLEDGEMENTS

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