Advanced Kinematic Cardboard Prototyping for Robot Development

Won-Sup Kim

Seoul National University of Technology, Department of Industrial Design
Korea, wskim@snut.ac.kr

Abstract: This paper provides a framework for a more effective cardboard prototyping tool to use in the robot design process. The object of the robot design prototyping framework is to supply the appropriate prototyping methods for each stage of the robot design process by changing materials, supplies, and modeling tools. The method effectively reflects the initial design concept in the final production without omissions or changes. To increase the fidelity of kinematic cardboard prototyping at the engineering level, improvements in accuracy and stiffness are needed. The concept of a framework in this paper denotes a system that connects prototypes at each stage of the robot design process and produces a final model from the results of each developmental stage. By combining of kinematic cardboard prototyping and digital work, integrated development using prototyping is possible throughout the robot design process.

Key words: Robot Design, Prototyping, Kinematic Cardboard Prototyping, Integrated Design.

1. Introduction

Designers' roles are limited in the development of robots. Despite the expansion of design research on human-robot interaction (HRI), design is still subordinate to engineering in the development of robot hardware. Because robots have some freedom of physical motion with their hardware structures, the designers' work is limited to the robots' appearance or style [1, 2, 3]. Sometimes, talented robot engineers integrate their engineering developments and styling [4, 5]. When designing a robot by integrating engineering and styling, the developers have advantages in the design process because they can consider both the engineering constraints and the styling requirements simultaneously. As a result, they can decrease development time and cost as well as propose more creative solutions.

Traditional frame-structure-based heavy robot platforms are not efficient in terms of weight, space, and interference. Thus, high-performance robots, such as humanoid robots, are designed with light-weight platforms [6]. For increased efficiency in robot performance, the hardware platform should be designed based on a monocoque frame structure similar to those used for vehicles. So a development method that integrates engineering knowledge and an aesthetic approach is necessary to design today's robots. But there are only a few robot designers who can integrate technical knowledge and design skills. Moreover, this method is not suitable for team-work or huge projects. For more general applications of this integrated method for robot design, a wide range of tools is needed.

In this paper, a prototype tool, one that can be a common development and communication tool for both engineers and designers, is modified for the robot development process. I also propose a robot design framework and detailed guidelines for applications.

2. Related Works

2.1 Traditional Robot Prototyping

2.1.1 Form Prototyping for Idea Generation

Form prototyping is a common practice in the early stages of the mechanical engineering development process [7]. Form prototyping is quick and depends on the developers' new ideas. Using this prototyping, developers can construct a real scale form. This prototyping is also effective for communicating ideas among developers, for example doll armatures that are the skeletal frames for stop-motion animation characters and models [8].

2.1.2 Working Prototyping Using Pre-Designed Kits

Pre-designed and pre-supplied mechanical kits are universally used in robot prototyping, starting with a virtual concept model. These kits are also it used in mechanical design development that incorporates the experience of hands-on activities. The worldwide standard robot mechanical kits are LEGO's *Mindstorms* variations. In earlier mechanical concept development stages, a simpler mechanical design tool like Hornby's was used. Mechanical kit toys, such as *Meccano,* are still appropriate. LEGO, Fischertechnik, K'NEX, Erector Set, Robotix, and Capsela have advantage in training the developers of robot structures. In recent years, a simple assembly kit using a notebook computer was developed. These robot kits consist of functional modules and, by mixing these modules, we can increase the functions of robots.

2.1.3 Ready-Made Robots for AI Development

Ready-made robots are used in research-related artificial intelligent (AI) or software development as service robots. Some robot developers can fine-tune a ready-made robot to meet their objectives. Robot kits are ideal for robot developers who do not like the construction aspects of robotics, but instead want to concentrate on electronics or programming. These developers prefer OWIKITS and MOVITS, which are precision-made miniature robots in a kit form.

2.1.4 Cardboard Prototyping

Having a cardboard prototype body is an effective method for fast robot prototyping. Erik Zoltan quickly created his robotic prototype in a couple of hours using only old boxes, a knife, scissors, and a glue gun [9]. This is an effective technique for robot prototyping, though it does not a produce a sturdy prototype. But to developers, it is an advantage to constantly rip out parts and replace them with slightly improved alternatives. Whenever something is broken, it can be repaired usually with only a glue gun. It is possible to make cardboard products that have sufficient compressive strength to carry structural loads. So cardboard can be used to make a working prototype. Figure 1 shows a hand robot using cardboard [10]. Cardboard prototyping with laser cutting is a better alternative than three-dimensional (3D) printing. The frame was designed using a press-fit assembly method.

Pieces of wooden dowel were added at the joints to strengthen them. Actuator and motion control boards can be added on the cardboard frame.

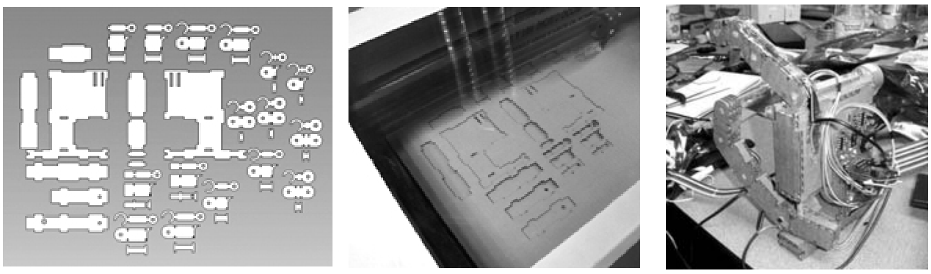

Figure.1 Hand robot cardboard prototypes from CAD work

2.2 Traditional Design Prototyping

Model can be classified into two groups, according to work style [11]: reproduction models and design models.

- Reproduction: Shapes and dimensions are determined first and then put into model form.
- Creation: The focus is on representing an image rather than achieving dimensional precision. Model production is shape creation.

Prototyping during the early design process is a supporting tool for the designer's creative activity. High-fidelity prototypes are used in the late design process for deciding the final model. So the designer's work style during the final stage of the design process is the so-called reproduction activity. Design prototyping consists of various types. Software-related prototypes have no connection with the styling process, and therefore these prototypes are not included in this paper. Only form-based prototypes are reviewed. In this paper the prototypes for product design are classified into six categories: sketch, dummy mock-up, finished mock-up, kinematic card board prototype, mechanical working prototype, and virtual model. These categories are based on the analysis of the images gathered from a Google image search and such books –as *Design Secrets: Products* [12] and *Design Secrets: Products 2* [13]. Some prototype styles that have no shape were removed from this classification, for example, the paper prototypes for user interface research. Table 1 shows the properties of each prototype for product design.

Table 1. Properties of design prototype

	Fidelity	*Building Cost*	*Building Time*	*Item Difficulty*
Sketch	Low	Cheap	Short	Easy
Dummy Mock-up	Low	Cheap	Short	Easy
Finished Mock-up	High	Expensive	Long	Difficult
Kinematic Cardboard Prototype	Low	Cheap	Short	Easy
Mechanical Working Prototype	High	Expensive	Long	Difficult
Virtual Model	Low-High	Cheap	Long	Difficult

2.3 Constraint for Development of Robot Prototyping

2.3.1 Problems in Robot Prototyping

Today, the general prototyping method for robot platform development is a pre-designed kit consisting of module format components. The recent robot development trend uses the physical prototype form of the virtual prototype after computer simulations. Using a digital mock-up, developers can quickly build dynamic locomotion patterns [14]. But the realization of performance is the main objective of robot development. Thus robot prototypes are aimed at the materialization of a verified concept, moving from a virtual space to the real world. For these reasons, developers are good at using pre-designed kits or ready-made robots to save time and costs, and these savings pay for the development of new hardware components. But pre-designed kits limit the developer's creativity, so these tools are disadvantageous for form development. When using a commercial tool, it is hard to connect form design, mechanisms, and creative structural design.

2.3.2 Prototyping Efficiency in Robot Design Process

The robot prototyping environment consists of several subsystems, such as design, simulation, control, monitoring, hardware selection, CAD/CAM modeling, part ordering, physical assembly, and testing [15]. Robot prototyping has to satisfy many engineering needs. The key point of this paper is how to efficiently connect design factors with other engineering factors. The design factor should be closely linked with the prototype.

The general design process includes the styling process, and the engineering design process has a spiral evaluation structure consisting of design, build, and test [16]. The results of the engineering evaluation process accumulate to next stage. But the styling result is renewed at every stage by changing the engineering functional requirements (FRs) (Figure 2). The most important factor in styling prototyping is the appearance parameter. The styling result is renewed not only as content but also as a format for design evaluation. Thus, different types of prototyping are used at every stage of the traditional styling process.

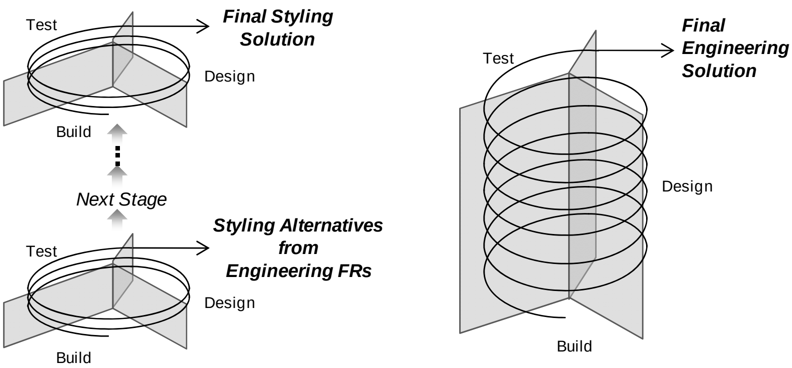

Figure.2 Styling evaluation process (left) and engineering evaluation process (right)

"Cheap" and "fast" are two important rules for prototyping [17]. But, other factors are needed at each stage of the robot design process. Table 2 shows the factors for prototyping at each stage.

Table 2. Prototyping in needs during the robot design process

Stage	*Problem Definition*	*Conceptual Design*	*Hardware Platform Construction*	*Programming*	*Field Test & Modification*
Needs for Prototyping		• Easy to build • Cheap • Fast construction • Mechanical working	• Mechanical working • Stiffness • Standard components attachable • Easy to assemble		• Mechanical working • Stiffness • Accuracy • Reassemble

Figure 3 shows the efficiency of the general design prototypes in the robot design process.

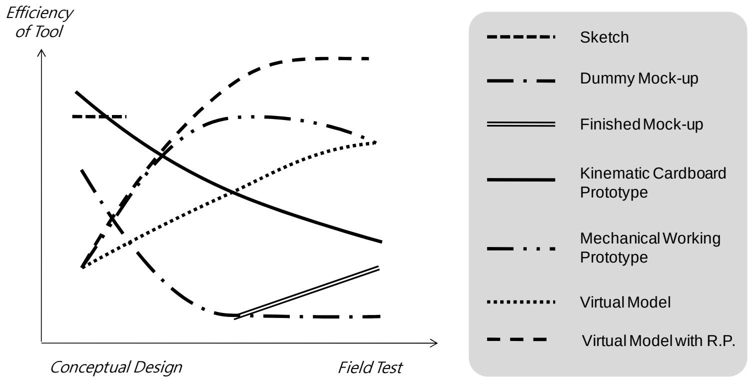

Figure.3 Prototyping efficiency in the robot design process

Prototyping cannot satisfy the needs during each stage of robot design. This paper focuses on how to step by step increase the efficiency of kinematic cardboard prototyping, or how to make the virtual model easy and fast (Figure 4).

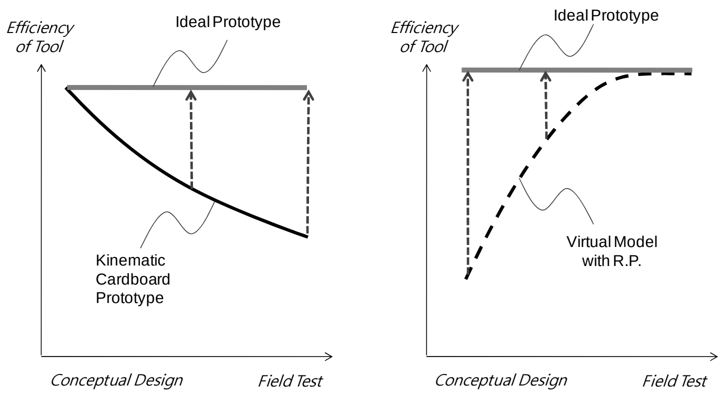

Figure.4 Efficiency increase of prototyping in robot design process

3. Development of Prototyping

3.1 Framework for Root Prototyping

The concept of a styling framework is a protyping system connecting prototyping at each stage of the robot design to process to produce a final model. Each prototyping link in the evolution system is combined with the material information and the manufacturing method (Figure 5).

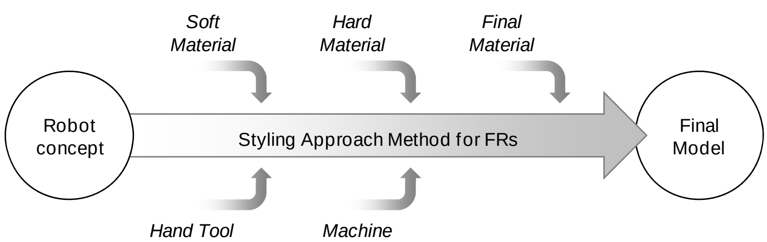

Figure.5 Framework concept of robot prototyping system

Despite the advantages of cardboard prototyping, some improvements are needed for more effective robot design. Cardboard prototyping has some weaknesses, starting with the engineering test in robot development. This prototyping has no accuracy because the model is built by hand. And another weakness is stiffness caused by the materials. By using kinematic cardboard prototype into the late stages of robot design, accuracy can be increased. However, material changes are needed to increase stiffness of prototypes. After this process the card board prototype will ready to field test (Figure 6).

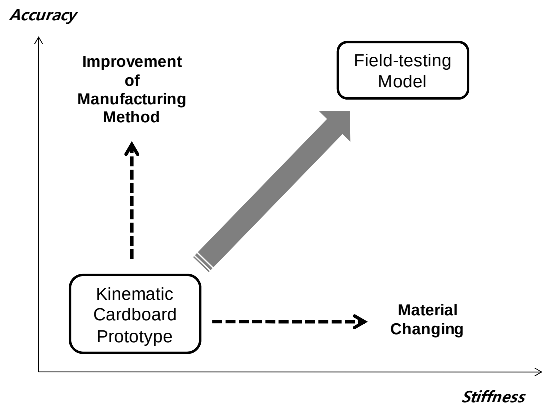

Figure.6 Concept of cardboard prototyping improvement

Kinematic cardboard prototype evolved through the improvement of stiffness as materials changed. The current kinematic cardboard prototype was generally improved by connecting with computer-aided design (CAD) modeling. A virtual model from CAD can be used to build a prototype of a final model, considering the real world from the physical prototype. Between the physical prototype and the virtual prototype, each prototype is improved by effected mutually (Figure 7).

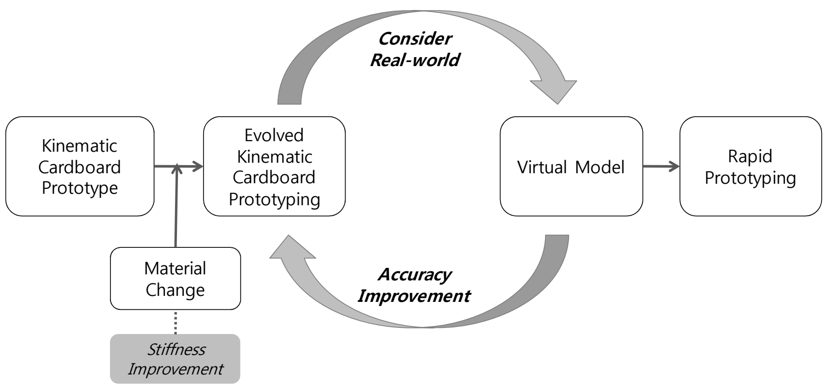

Figure.7 Circulation of mutual improvements of prototypes

From this increase of prototyping fidelity, a prior prototyping tool can be used at a late stage. As this prototyping contains the initial design concept, it will be a more effective tool than any other prototyping used at the late stage (Figure 8).

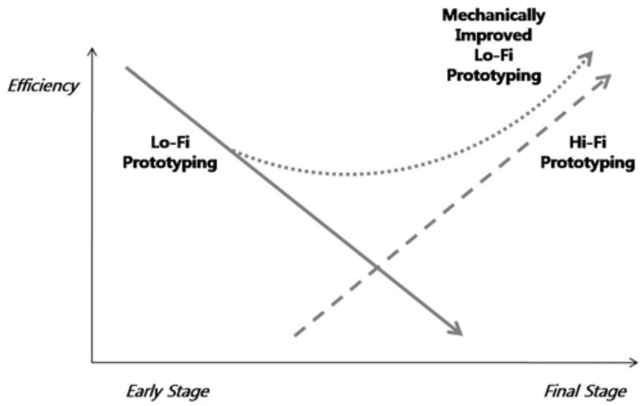

Figure.8 Increase of prototyping efficiency through mechanical improvement

From the coupling of kinematic cardboard prototyping and digital work, ceaseless development through prototyping is possible throughout the robot design process. Mechanical improvements such as increasing accuracy and stiffness can be made so that the low-fidelity kinematic cardboard prototyping will become more powerful. This is the concept of a robot prototyping evolution system (Figure 9).

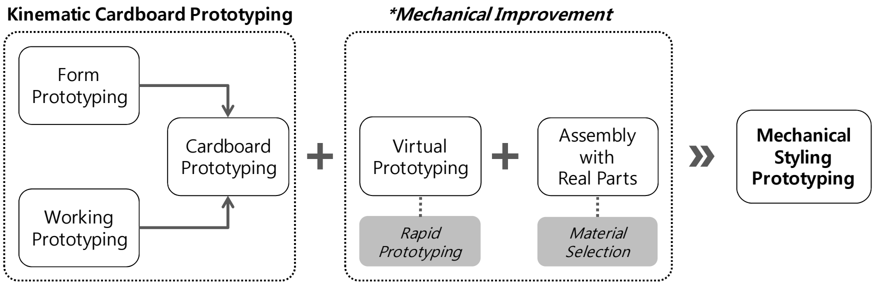

Figure.9 Concept of a robot prototyping evolution system

3.2 Robot Prototyping Framework

Considering the condition of the robot process, the cardboard prototyping framework consists of three parameters: constant parameters (CPs), variable parameters (VPs), and additional parameters (APs) (Figure 10).

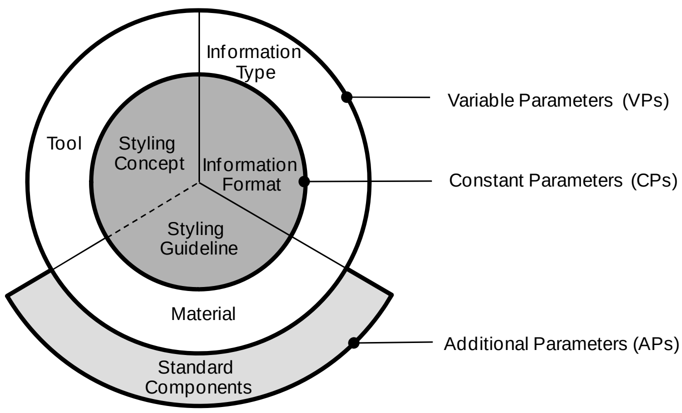

Figure.10 Design parameters (DPs) for robot prototyping

CPs are unchanged factors throughout the process like styling concepts, styling guidelines, and information format. CPs are the main factors linking each prototype to a systematic framework. Owing to CPs, robot engineers and designers can efficiently approach every type of robot platform during the development process. VPs are changed factors between earlier stages and the following stages. Materials, tools, and detailed information are included in the VPs. From the exchange of the VPs, fidelity of prototyping increases. APs are new supporting factors when the next stage starts. Factors of APs are an actuator for motion and other standard components for structuring. These factors are necessary in prototype working and manufacturing. These three types of parameters are the action factors to practice platform prototyping using DPs for mechanical FRs. The designer evolves a prototype from a concept to a final solution through the Robot Cardboard Prototyping System (Figure 11). As cardboard prototype is evolved following design process, robot platform is developed concurrently.

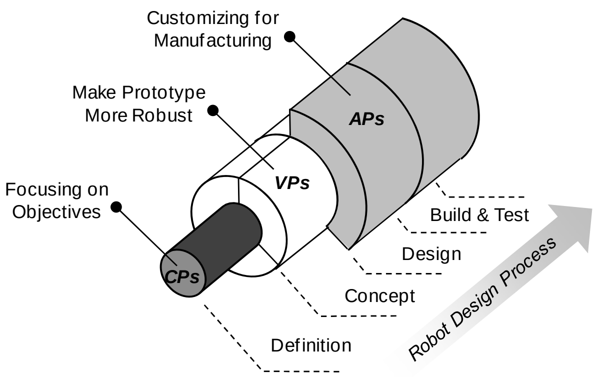

Figure.11 Robot Cardboard Prototyping System

3.3 Implementation

In this paper, two cases of the implementation of kinematic cardboard prototyping are introduced. First, a high-fidelity styling prototype is suitable in between the conceptual design stage and the hardware platform construction stage.

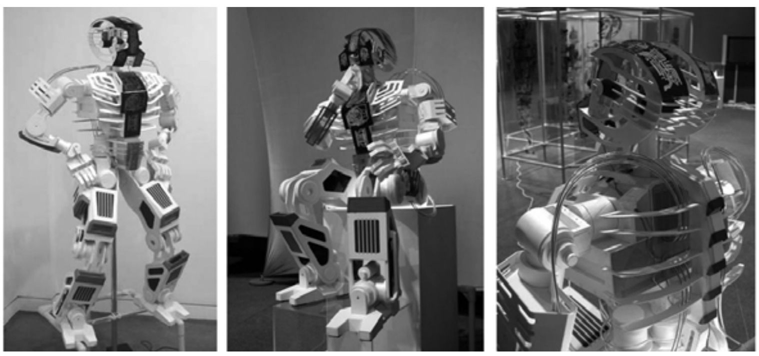

Figure.12 High-fidelity styling prototyping using cardboard

The robot prototype in Figure 12 is the result of styling-centered prototyping. This prototype was moderate and comparatively easy to produce. Designers can improve the production speed by connecting numerical control (NC) equipment. The robot was built with a focus on appearance. But this robot has many exposed inner frames.

Thus its appearance design is based on mechanical drawings. Its frame components were designed considering engineering jointing and bolting. In this prototyping, gluing replaces bolting. Other components having an organic form are the result of design considered machining properties. Physical prototypes were verified for real sizes and volumes, interference in moving, and an array of inside components and wiring. These factors are not easy to evaluate in virtual model. It is easy to modify forms in this prototype. Like a real-sized clay model, components are easy to cut and replace. Furthermore, this prototype is very cheap.

The second prototype is a high-fidelity mechanical prototype suitable for the field test and modification stages. In general, this prototype was developed from a high-fidelity styling prototype.

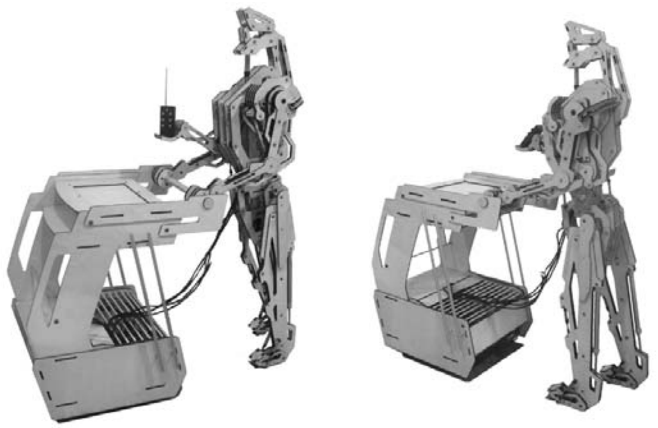

Figure.13 High-fidelity performance prototyping using cardboard

The robot main frame in Figure 13 is made of plywood boards, and is operated by five small geared motors. Improvements can be made in this robot such as the communication function by attaching simple equipment. This prototype was designed as a low-priced practical consumer robot that performs guided and publicity activities. This prototype evolved from a styling prototype in to a final model after materials were exchanged and additional standard components were connected.

4. Conclusion and Discussion

Cardboard prototyping is efficient tool for robot platform design. Prototyping tools, advanced kinematic cardboard prototyping, increased stiffness and accuracy from optional materials and CAD support direct and easy solution were all used to build the final version of this robot. The improved prototyping proposed in this paper is a system that constructs a series of kinematic cardboard prototyping over the whole robot design process. This system includes optimal tools, materials, and approaching methods in each design stage. The prototyping framework in this paper has two merits in support of efficient robot platform design:

- *Simple Process*: The traditional robot hardware design process is divided into two sub-processes: an engineer's process and a designer's process. The trade-off method uses traditional processes weakly linked to each other. By using an effective prototyping, the two separate processes can be integrated.
- *Minimum Information*: This is prototyping for robot styling using minimal information for manufacturing during the development process. Even if all prototypes are in same styling format, each

prototype performs the roles according to requirements at each stage with the fewest additional components.

This prototyping system can be improved in its styling aspects for modern robot design in order to have an organic and emotive appearance.

5. References

[1] Kim, W.S. (2007) The Design of Humanoid Robot Platform: HUBO, *Journal of Korean Society of Design Science*, vol. 20, no. 6, pp 13-16.

[2] Hong, S.S., Heo, S.C., Kim, E., and Chang, Y.J. (2006) A Study on the Practical Human Robot Interface Design for the Development of Shopping Service Support Robot, *Journal of Korean Society of Design Science*, vol. 19, no. 4, pp 81-90.

[3] Yang, S.H., Byun, J.H., and Seo, J.H. (2008) The Design of Kids Robot: raBie, *Journal of Korean Society of Design Science*, vol. 21, no. 6, pp 79-82.

[4] Matsui, T. (2005) The Roles and Method of Robot Design. In *Proceedings of Robot Design Forum*, RDF 2005, pp 47-55.

[5] Takahashi, T. (2007) Emotional Robot Design. In *Digest Book of IEEE RO-MAN 2007*, IEEE RO-MAN, p 52.

[6] Albu-Schäffer, A., Haddadin, S., Ott, Ch., Stemmer, A., Wimböck, T., and Hirzinger, G. (2007) The DLR Lightweight Robot: Design and Control Concepts for Robots in Human Environments. *Industrial Robot: An International Journal*, vol.34, no. 5, pp.376-385.

[7] Menzel, P. and D'Aluisio, F. (2000) *Robo Sapiens,* 1st Ed., MIT Press, Cambridge, pp182-185

[8] McComb, G.. (2003) *Robot Builder's Sourcebook*, McGraw-Hill, New York, p 438.

[9] Zoltan, E. (2007) Wireless robotics: Fast robot prototyping. Available at <http://www.ibm.com/developerworks/kr/library/wi-robot3/#N1005A> [Accessed 22 October 2007]

[10] Taylor, Z. (2007) How to Make (Almost) Anything / Final Project: Cardboard Pincher. Available at <http://fab.cba.mit.edu/classes/MIT/863.04/people/ztaylor/> [Accessed 22 October 2007]

[11] Yamada, Y. (1997) *Clay Modeling: Technique for Giving Three-dimensional Form to Idea*, Car Styling, Tokyo, p 7.

[12] IDSA (2001) *Design Secrets: Products*, Rockport Publishers Inc., Gloucester, Massachusetts.

[13] Haller, L., Cullen, C. D. and IDSA. (2006) *Design Secrets: Products 2*, Rockport Publishers Inc., Gloucester, Massachusetts.

[14] Frutiger, D. R., Bongard, J. C. and Iida, F. (2002) Iterative Product Engineering: Evolutionary Robot Design, in Bidaud, P. and F. B. Amar (eds.), *Proceedings of the Fifth International Conference on Climbing and Walking Robots*, Professional Engineering Publishing, pp 619-629.

[15] The Interdisciplinary Robotics, Intelligent Sensing, and Control (RISC) Laboratory at the University of Bridgeport, Introduction to Robotics Class Notes. Available at <http://www1bpt.bridgeport.edu/~risc/> [Accessed 22 October 2007]

[16] Ullman, D.G.. (2002) *The Mechanical Design Process*, McGraw-Hill Science, New York, p 180.

[17] Introduction to Mechatronics. Available at <http://design.stanford.edu/Courses/me118/> [Accessed 22 October 2007]