Rapid Prototyping Spiral for Creative Problem Solving in Developing Countries

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***Abstract*—In this paper, we focus on how we can assist the local designers in the developing countries to design and manufacture the problem solving products. Although there are a lot of examples of appropriate technology, most of them were designed by the experts who have professional knowledge. To solve this issue, we propose a design method *rapid prototyping spiral*, considering the conventional studies on creativity support. The rapid prototyping spiral is a quick iterating process of creating prototypes and getting feedbacks from the users. The advantage of this method is that it enables the designers to discover the hidden issues or the unconscious assumptions underlying the users or the community. Our method also takes advantage of the limitation of materials, which has been regarded as a negative aspect so far. We illustrate how our method is applicable to design in the developing countries, taking a project in Ghana as an example.**

Keywords-Design method; Prototyping; Design space.

I. INTRODUCTION

A. Problem solving products in developing countries

Creating the innovative product to solve daily problems gives great impact especially to the people in the developing countries, where they are exposed to severe constraints. One of the famous activities to make these products is the *appropriate technology*. The appropriate technology is an application that is small-scale, labor-intensive, energy-efficient, environmentally sound, and locally controlled [1]. A well-known example of the appropriate technology is Q Drum, a plastic water tank which can be easily moved with its rotation [2].

B. Assisting local designers

So far, the designers of these problem solving products needed to understand the culture and the situation in the area they are targeting thoroughly since they were usually the outsiders of the community. To achieve this purpose, for instance at the d.school in Stanford university, various methods were invented for the designers to discover the local needs efficiently. To identify the essential needs in the developing countries, the framework of the *participatory development* was contrived in the field of the international development, which proceeds the project through interaction with inhabitants [3]. The *inclusive design* concept is also similar, to include the people, such as physically challenged people, into the design process to identify the socially important needs [4]. On the other hand, in terms of sustainability, it is also important to establish the environment for the local designers to design the product by themselves. For example, the tutorial to make some appropriate technologies is provided online for the local people to recreate the products by themselves, which is called Open Source Appropriate Technology (OSAT) [5]. Moreover, in the *Fab lab*, the worldwide open workshop which provides the digital fabrication tools to the people in the community, local designers have produced some useful products. For example, the Fab-Fi, the low cost Wi-Fi antenna for building the Internet mesh network, was developed in the Fab lab Jalalabad in Afghanistan [6]. Despite the increase of those platforms, the authors believe there still are plenty ways to accelerate the creation of the problem solving products in the developing countries. In this paper, as shown in Figure 1, we propose the design method and the support system for local designers to create the problem solving products by themselves.

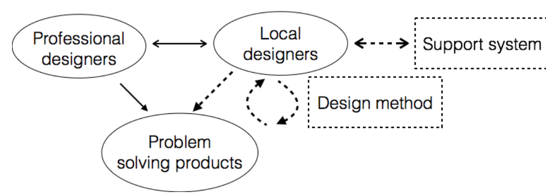

Figure 1. Design method and support system for assisting local designers

First of all, in Section 3, we discuss the existing difficulties that local designers face and clarifies the requirements for creating the design method. Considering the result, we propose the design method based on our past projects in Section 4. Moreover, we present the support system for assisting the design using our method in Section 5.

II. RELATED WORK

A. Appropriate technology

A lot of products of the appropriate technology have been invented and currently in use [2]. For example, a solar cooker is a device to generate heat using solar power as an energy source. People can make the reflector of the solar cooker with an unused parabolic antenna, which is an example of using materials in a different way. Other example is a hydraulic ram, a kind of water pump which can lift the water to a higher point without any external energy source. The hydraulic ram is interesting because it is based on a simple principle of fluid dynamics, which is the water hammer. These products were designed by the experts who have the knowledge of each domain, therefore we aim to involve more local people in the design of such products. In this perspective, some successful products designed by ordinary people in South Asian countries have got attention. These products are called as frugal innovation or *Jugaad*, which means a creative problem solving with improvised arrangements [7]. For example, a hand-made vehicle was invented by local inhabitants using the agricultural water pump. Although there are such cases of the design by local people, there seems to be little researches on the design methodology and the support system for it.

B. Prototyping for creating ideas

One of the key issues of creating the problem solving products is to identify the needs of local people correctly. Some studies clarified the effectiveness of the prototyping for discovering the personal needs. Lim et al. pointed out their unique prototyping method called Discovery-Driven Prototyping (DDP) promoted discovering underlying issues of individuality [8]. Kelly also mentioned the importance of the prototyping in the problem solving [9]. So far, the prototyping of hardware has taken a long time; however, the recent developments of the fabrication tools drastically changed the environment around amateur creators. A 3D printer enabled the production of the plastic parts with less cost and time. With a laser cutter, the creators can cut the wooden or acrylic board in precise dimensions. Moreover, the micro controller board such as Arduino enabled users to prototype the electronics much easily [10]. Using such micro controller board, users can try various combinations of sensors and actuators to explore the design solution. We implement the support system using those fabrication tools effectively. It is important to support both conceptualisation and manufacturing in the design process since our targets are local designers, who usually don't have much knowledge and experience in design and manufacturing.

C. Creativity support

Boden described the three forms of creativity [11]. The first one is the combination of familiar ideas in unfamiliar ways. The second and third are the exploration and the transformation of conceptual space. Gero divided the design into the three types: routine design, innovative design and creative design [12]. Their arguments seem similar if we define the creative design as the transformation of conceptual space. Finke et al. discussed the creative activity based on the psychological experiment [13]. They proposed *geneplore model*, which demonstrates that the creative process is a cyclic process, which consists of generation of preinventive structure and preinventive exploration and interpretation. Although such theoretical researches and the laboratory experiments exist, there are a small number of practical studies on how to assist local designers to make the problem solving products in developing countries. Based on those preceding studies, we propose the design method, which promotes the exploration of the design space through the continuous prototyping.

III. Requirements Analysis

A. Identification of needs

It may seem easy for a local designer to identify the needs in a community, and no special design method is necessary to identify the needs. However, from the experience in the past project, we propose a design method is required not only for external designers, but also for local designers. In 2010, the authors engaged in the project with a Non-Governmental Organization (NGO) to develop a movie material of the science experiment for enhancing the educational quality at a farm area in Bangladesh. The movie was shot in the high school known for its high educational level. Contrary to expectations, the created movie was not good enough to be published in terms of the quality of the content, mainly because of the lack of the safety instruction by the teacher. The interesting point was that, prior to making the pilot movie, no one in the local NGO was suspicious of the quality. In this sense, making the prototype enabled us to realise the hidden assumption in the community, which was the less awareness of the safety education. However, the more interesting point was that one of the members in the NGO finally proposed to reuse the movie for the teachers not for the children, in order to enlighten the teachers about the importance of safety instruction. We point out it is a good example of the transformation of the product use to a different way. Every single person, no matter where he or she is from, has the personal bias based on the experience or cultural background, which unconsciously regulates his or her thoughts. Liberating designers from those unconscious constraints makes it possible to explore the different solutions unexpected at the initial phase in the design process.

B. Considering limitation of materials

In general, manufacturing resources, such as materials and tools, are limited in the developing countries. These constraints sometimes make designers give up using specific material. However, the limitation of materials sometimes promotes designers to come up with an innovative way of solving problems. For example, in our project in Ghana, we have been forced to select a wooden board rather than metal for making a magnetic rotor because of the availability. As a result, the choice enabled us to make the parts easier and with less cost. In another instance, the Jaipur Foot, a prosthesis foot developed in India, uses locally available rubber which satisfied the various requirements at the same time, such as the resemblance to the appearance of normal human foot, durability, waterproofness, and affordability [14]. The product diffused from India into parts of the world, which is opposite of the conventional technology dissemination. Recently, the movement of these inventions is referred as the reverse innovation [15]. Regarding this, we need to focus on the positive aspect of the limitation of materials.

C. Manufacturing knowledge

The open source software and hardware made it easier to develop the products with less cost, time and human resources. Besides, the online tutorial, such as *Instructables*, also enabled the sharing of knowledge and skills of the manufacturing. However, so far the designer of the appropriate technology was the expert who has the fundamental understanding of the technology. Since we aim to assist the local designers including amateurs, not only providing knowledge but also supporting the utilization of the knowledge is required.

IV. Design Method

A. Definition of design space

Conventional design studies provided several ways for describing design space to discuss design process. For example, Maher et al. presented the co-evolution model, which describes the design exploration as the interaction of problem space and solution space [16]. As shown in Figure 2, we split the design space into four layers which are problem space, function space, structure space, and tool and material space. The problem space consists of the needs of the product users. The function space involves the required function of the products. The structure space is the collection of the entities which materialises the given functions. The tool and material space represents the whole available materials and the facility of manufacturing including machine tools. This separation concept is similar to the design model proposed by Suh [17]. In particular, we focus on the feedbacks from the tool and material space to the other spaces, which we believe is the unique feature of production in the developing countries. Due to the limited resources, the exploration of the suitable structure is regulated by the locally available materials. We use this design space model to discuss the transformation of each space during the design process.

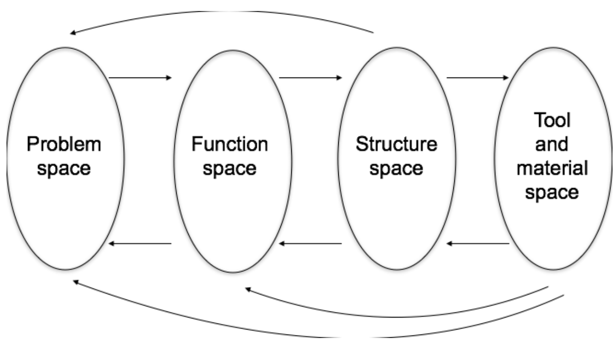

Figure 2. Definition of the design space

B. Dynamic transformation of design space

The main focus of the proposing design method is to transform the design space dynamically by the iteration of the prototyping. Here, we show the transformation of the design space taking the project in Ghana as an example.

In Figure 3, the solid arrows represent the initial flow of the designer's thoughts. In our project in Ghana, we initially targeted to solve the e-waste problem that was associated with the health hazard among the laborers who are working in the waste dump to extract metals such as gold and copper by burning the wastes. To avoid such problem, we defined the required function as the eddy current separation, which can separate the metals from plastics without burning the wastes. Subsequently, we picked up the sub functions of the eddy current separation as follows:

- Magnetic rotor to generate the electromagnetic field by the rotation of the magnets
- Power source for driving the magnetic rotor

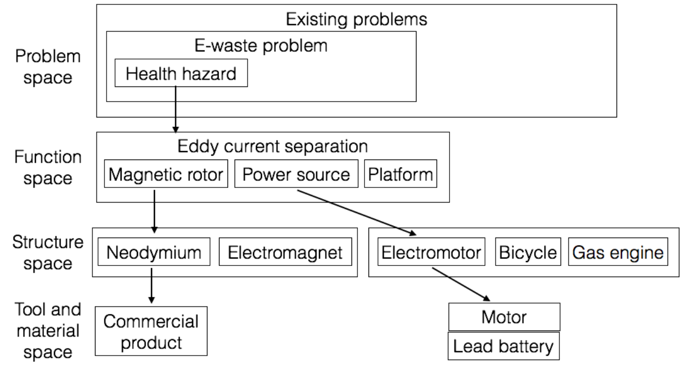

Figure 3. Design flow at initial state

- Platform to hold the magnetic rotor, a drive shaft, and bearings

Then, we started designing the magnetic rotor. At the beginning we expected to use the neodymium magnets, but later we noticed there were no neodymium magnets available in the local shops. After discussions, we decided to dismantle hard disk drives to extract the neodymium magnets. This transition of the design can be regarded as the extension of the tool and material space because we were able to discover the availability of the particular material through the design process. Such transformation is shown in Figure 4.

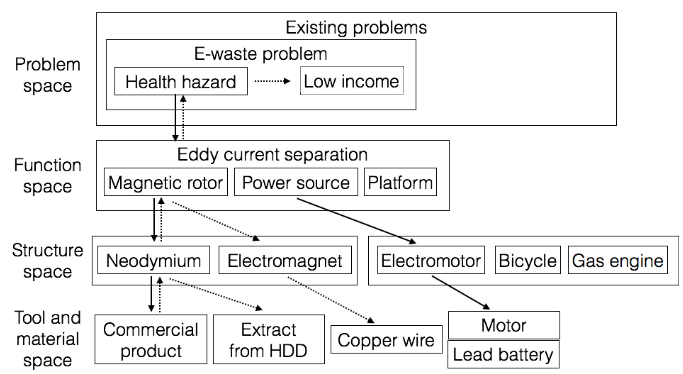

Figure 4. Transformation of structure space and tool-and-material space

In Figure 4, the dotted arrows show the flow of the induced thoughts through the prototyping process. In similar ways, each design space reflects on other design spaces, which triggers the transformation of the design space. Interestingly, as we mentioned the uniqueness of the tool and material space, the tool and material space can affect the problem space directly.

For example, as indicated in Figure 5, if we come up with the idea of using the electric motor and the lead battery to drive the magnetic rotor, it signifies that we are aware of the local availability of the lead battery. Then, we can start the discussion on the possible product made with the lead battery, which may lead to the use of the product to supply the electricity in the unelectrified area.

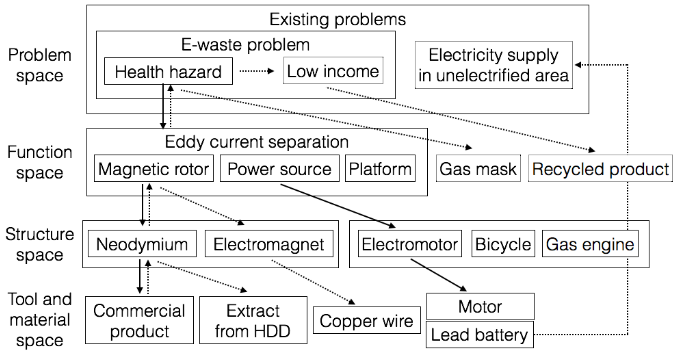

Figure 5. Transformation of function and problem space

C. Rapid prototyping spiral

Our focus is how we can accelerate the transformation of the design space. We propose the design method using the quick iteration of design, manufacturing the prototype and testing, which we call *rapid prototyping spiral*. The significance of prototyping is described in the design field from various perspectives. For example, Thoring et al. mentioned that the iteration of prototyping enables designers to find the next problem, while explaining the process of the design thinking [18]. In Figure 6, our design method is shown compared with the design thinking process.

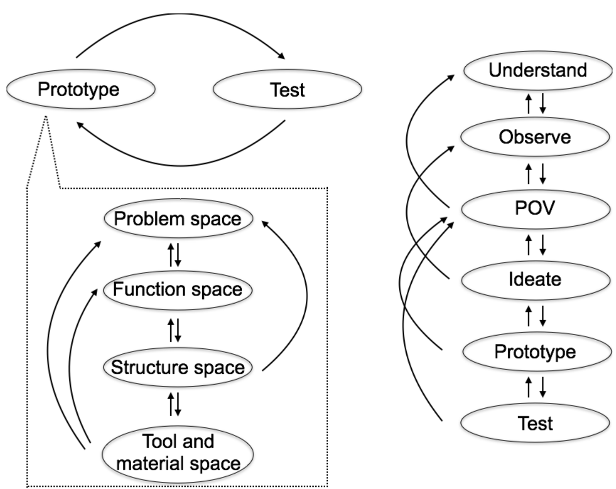

Figure 6. Prototyping spiral compared to the design thinking (used the figure from HPI D-School as reference [18])

In Figure 6, the left part shows our rapid prototyping spiral, and the right side represents the design thinking process. As shown in the figure, we propose to start the design process from prototyping. The reason we changed the order in the design process is that we focus on the following three aspects, which should be considered when assisting local designers in the developing countries.

- Limitation of materials
- Intrinsic motivation
- Production of practical products

TABLE I. EXPLORATION OF FUNDAMENTAL PROBLEMS

Design phase	Problem space	Prototype
Initial phase	Low quality of science education Lack of resources	Science movie shot in the high-level school
Second phase	Lack of carefulness for safety instruction	Material for teachers to instruct safety

First, due to the limitation of materials, local designers may not be able to manufacture the product with the materials required in the ideal design. In our method, by starting the design process from prototyping, the designers are promoted to focus on the material space mentioned in the previous section, and it leads to the exploration of the unexpected use of materials. Second, we expect that the continual process of the materialisation motivates the local designers, and such motivation enhances the creativity in the design process as indicated in the conventional researches [19] [20]. Third, the problem solving in the developing countries requires not the conceptual but the practical outputs as materialised things. Although the primary role of the prototype in our design method is an explorer of the design space, it is also aimed to be used as the real solution at the same time.

V. SUPPORT SYSTEM

We propose the support system to assist the design using our method. The support system consists of following four components.

A. Exploration of fundamental problems

What makes our design method differ from the conventional product development is the transformation of the initial problem space during the design process. The purpose of transforming the problem space is to find out the fundamental problem, in which the initially addressed problem is rooted. We illustrate this feature by taking our project in Bangladesh as an example. As shown in Table I, we assumed the initial goal as creating the science movie to compensate the experimental environment at the farm area, which ended up revealing the relative incautiousness of the safety instructions even among the teachers at the school in an urban district. To accelerate such discovery of the fundamental issues, the iteration cycle of the prototyping will be effective.

B. Knowledge base of available materials and tools

The advantage of making knowledge base of the locally available materials is that it enables users to try the alternative solutions when the expected material is not available. The knowledge base is also helpful for reducing manufacturing time. For example in our project in Ghana, we faced difficulties regarding materials. When we looked for the metal shafts and pulleys, it took so much time to get the suitable ones because the local shop did not always stock fixed kinds of products. In this case, because the shops were concentrated in a specific commercial area, it was better to create the inventory for the whole area in advance. With the knowledge base, the designers can run the prototyping process more quickly. Furthermore, making the knowledge base of the available tools is also worthwhile. Although the fabrication tools are limited in the developing countries in general, each situation is inhomogeneous definitely. In our project in Ghana, we were able to use a laser cutter and a large CNC (Computer Numerical Control) milling machine, which seemed unusual equipments compared to the ones in the surrounding areas. The authors define those irregular environments as *technological spike*. We expect to create the products which are adaptable to the locality, by making the knowledge base of the tools including these technological spikes.

C. Knowledge base of manufacturing

The manufacturing knowledge base is required to support the innovative design [21]. Existing knowledge base to support the ordinary creators, such as Instructables, includes the list of the required materials and tools, and the description of the each process of manufacturing. Additionally, we propose to add the feature that the user can append additional knowledge on the different layer of the description. The additional knowledge is the knowledge discovered during the design process, for example, the description of a material which is different from its ordinary usage. Although the general documentation is expected to be simplified and include the least information required, we assert that these redundant information is valuable.

D. Archiving format of prototyping

We suggest the archiving format to describe the design process as shown in a following figure.

Prototype	Version 1 	Version 2 	Version 3 	...
Problem space				...
Function space	Unstable rotation	Magnets fly apart		...
Structure space	Eccentricity of the rotor Asymmetrically-distributed casings	Covered circumference of the rotor with plastic sheets		...
Tool and material space	Less cutting accuracy	Use large CNC milling machine	Use an oil can to cover the rotor	...

Figure 7. Archiving format of the prototyping

With the format shown in Figure 7, we are able to describe how each prototype affected the four design spaces. The reason why we relate the transformation of design space to each prototype is because it enables us to track such transformation in a chronological order. In the words of software development, this archiving format corresponds to the revision control.

VI. Ongoing Experiment

In this section, we explain how our method is applicable for assisting the design and manufacturing in the developing countries. We introduce the ongoing experiment that we are currently preparing with the help of the Takoradi Technical Institute (T.T.I.). T.T.I. is a technical high school in Ghana, which has a Fab lab inside. In the Fab lab, students can use digital fabrication machines, such as a laser cutter or a CNC milling machine. First, we explain how the designers can identify the fundamental problems using our design method.

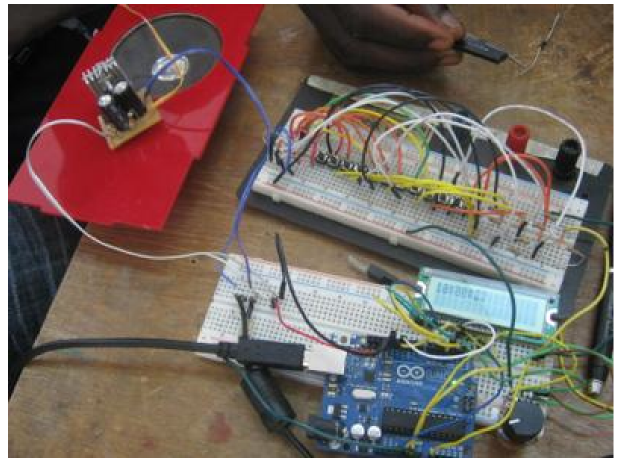

Figure 8. Sound alarm prototype

Figure 8 shows the prototype of a sound alarm made with our design method, which announces the beginning and end of the class to the teachers and students. It was based on the need of the principal, who told the authors the only one function to implement, which is emitting a sound triggered by a timer. The authors made the first prototype using Arduino, which plays a song at a scheduled time with electronic sound generated by a micro controller. The initial reaction of the teachers in T.T.I. to the prototype was different from expected, which was surprising to the authors. They demanded the authors to change the electronic sound to much louder and noisier siren. This feedback is noticeable because it changed the requirements specification of the prototype. Even though this observation is a slightly trivial example, by continuing to give feedback to the initial design space, we believe that the iteration process contributes to clarify the hidden assumption and fundamental problems.

Secondly, we introduce another example to discuss the transformation of design space. In this experiment, we set the goal as developing a 3D printer to produce inexpensive plastic parts. The expected transformation of design space is shown in Figure 9. In Figure 9, as well as the example shown in Section 4, the design proceeds from problem space to next spaces. A typical concept of a 3D printer using fused deposition method (FDM) is assembling an extruder of a plastic filament and a Computer Numerical Control (CNC) machine. Recently, the RepRap project allowed ordinary people to create a 3D printer by sharing all the information including 3D data of the parts and schematics of the circuit board [22]. Using such resources, in addition, we prepare the same mechanical unit for x, y, and z axes for building a CNC component. We take this module-based approach so that we can easily disassemble and reassemble it to build different machines. By creating different types of machines, we promote designers to discover unexpected functions of the machine. Also, in this example,

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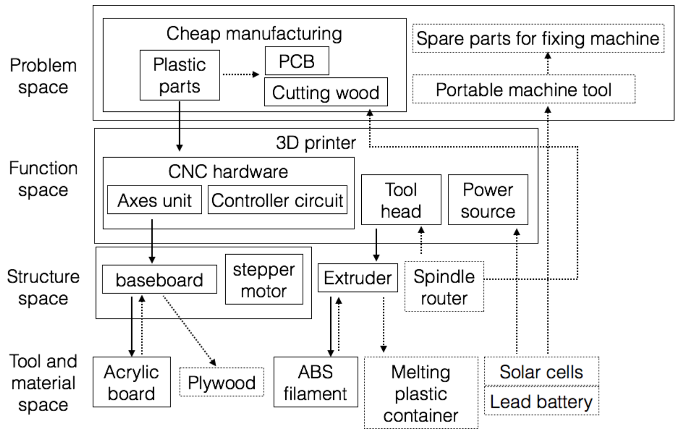

Figure 9. Expected transformation of design space

the tool and material space plays an important role. We try to use several materials, such as an acrylic board, plywood and even scrap wood, to find out the best choice in terms of cost and availability. The material space has an effect not only on the structure space, but also on the problem space. If a designer finds a lead battery, he or she may come up with the idea of powering the 3D printer by the battery. The customization makes the 3D printer portable, which can be regarded as the transformation of structure space. The portable 3D printer enables designers to take it to home and discover the possible use of it, such as creating the spare parts for fixing machines. This is an exploration of problem space, which is especially focused on the rapid prototyping spiral. After the whole design process, we analyse how the design space was transformed. When recording the design process, we utilize the web-based support system for archiving prototypes, as discussed in Section 5.

VII. Conclusion and Future Work

We proposed the rapid prototyping spiral, a design method for assisting the local designers in the developing countries to create the problem solving products. In our design method, the four kinds of design space are transformed during the design process, which enables us to discover the underlying issues in the users and the community, or come up with the unexpected usage of the materials. We also discussed the features of our support system to assist the design using the method we are proposing. As an example of applying our method to the design project, we introduced the experiment which is currently going on in Ghana. Based on the example of creating a sound alarm prototype, we observed a change of the requirement of a prototype, which induces the transformation of the design space. In addition, we introduced the design project to create a 3D printer, to prove the iteration of prototyping process contributes to identify more fundamental problems. We believe that the rapid prototyping spiral can also be applied to design and manufacture in the developed countries. The core of the method is supporting designers who have limited resources, such as materials, tools, and manufacturing knowledge. With the increase of the so-called maker communities and availability of digital fabrication tools, more individuals in the developed countries will be involved in design projects in the near future. We expect that our method also assists individual creators in the developed countries to identify the socially important issues, which leads to user-oriented innovation.

References

[1] I. Smillie, Mastering the Machine Revisited: Poverty, Aid and Technology. Practical Action, December 2000.

[2] C. E. Smith, Design for the Other 90%. Cooper-Hewitt Museum, 2007.

[3] V. Desai and R. B. Potter, The Companion to Development Studies. Hodder Education, 2008.

[4] S. Keates, P. J. Clarkson, L.-A. Harrison, and P. Robinson, "Towards a practical inclusive design approach," in Proceedings on the 2000 Conference on Universal Usability, ser. CUU '00. ACM, 2000, pp. 45–52.

[5] J. M. Pearce, "The case for open source appropriate technology," Environment, Development and Sustainability, vol. 14, no. 3, June 2012, pp. 425–431.

[6] N. Gershenfeld, FAB: The Coming Revolution on Your Desktop - From Personal Computers to Personal Fabrication. New York: Basic Books, 2005.

[7] N. Radjou, J. Prabhu, and S. Ahuja, Jugaad Innovation: Think Frugal, Be Flexible, Generate Breakthrough Growth. Jossey-Bass, April 2012.

[8] Y. kyung Lim, D. Kim, J. Jo, and J. bum Woo, "Discovery-driven prototyping for user-driven creativity," Pervasive Computing, IEEE, vol. 12, no. 3, August 2013, pp. 74–80.

[9] T. Kelley, "Prototyping is the shorthand of innovation," Design Management Journal (Former Series), 2001, pp. 35–42.

[10] J. Sarik and I. Kymissis, "Lab kits using the arduino prototyping platform," in Frontiers in Education Conference (FIE), 2010 IEEE. IEEE, 2010, pp. T3C–1.

[11] M. Boden, The Creative Mind: Myths and Mechanisms. New York: Basic Books, 1991.

[12] J. S. Gero, "Computational models of creative design processes," in Artificial Intelligence and Creativity, ser. Studies in Cognitive Systems, T. Dartnall, Ed. Dordrecht: Kluwer Academic Publishers, 1994, vol. 17, pp. 269–281.

[13] R. A. Finke, T. B. Ward, and S. M. Smith, Creative Cognition. MIT Press, 1992.

[14] D. H. S. Katherine Ott and S. Mihm, Eds., Artificial Parts, Practical Lives: Modern Histories of Prosthetics. NYU Press, April 2002.

[15] V. Govindarajan and R. Ramamurti, "Reverse innovation, emerging markets, and global strategy," Global Strategy Journal, vol. 1, no. 3-4, 2011, pp. 191–205.

[16] M. L. Maher, J. Poon, and S. Boulanger, "Formalising design exploration as co-evolution," in Advances in formal design methods for CAD. Springer, 1996, pp. 3–30.

[17] N. P. Suh, The Principle of Design. Oxford University Press, 1990.

[18] K. Thoring and R. M. Müller, "Understanding the creative mechanisms of design thinking: an evolutionary approach," in Procedings of the Second Conference on Creativity and Innovation in Design. ACM, 2011, pp. 137–147.

[19] E. A. Edmonds and L. Candy, "Knowledge support systems for conceptual design: the amplification of creativity," in HCI (2), 1993, pp. 350–355.

[20] T. M. Amabile, Creativity and Innovation in Organizations. Harvard Business School, 1996.

[21] J. C. Thomas, A. Lee, and C. Danis, "Enhancing creative design via software tools," Communications of the ACM, vol. 45, no. 10, 2002, pp. 112–115.

[22] R. Jones, P. Haufe, E. Sells, P. Iravani, V. Olliver, C. Palmer, and A. Bowyer, "Reprap - the replicating rapid prototyper," Robotica, vol. 29, no. 1, 2011, pp. 177–191.