3D Crossover: exploring *objets digitalisé*

Marc Aurel Schnabel, Thomas Kvan, Steve K.S/ Kuan and Weidong Li

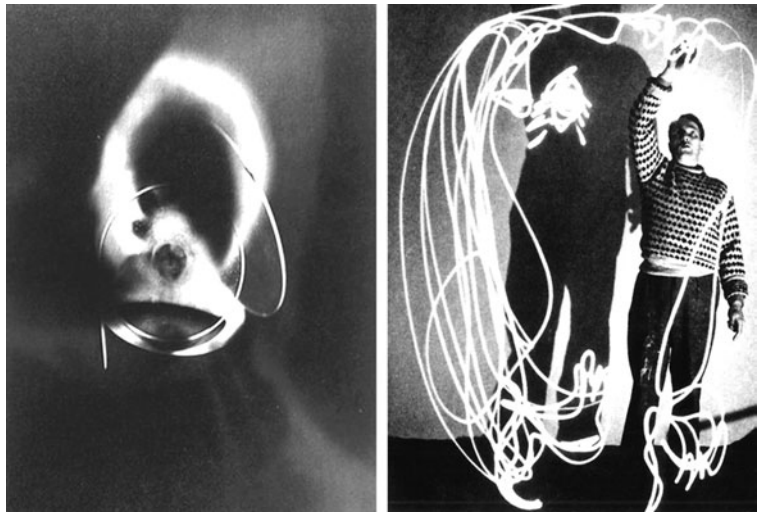
3D Crossover: exploring *objets digitalisé*

Marc Aurel Schnabel, Thomas Kvan, Steve K.S/ Kuan and Weidong Li

By merging a range of digital and physical media, the architectural design process is enriched by different perceptions, comprehensions and conceptions of spatial volumes within both physical and virtual environments. The use of digital media often confines the design process to only the digital realm; in this class, students moved fluidly back and forth from digital to physical using digital tools in unorthodox ways. These different media transformed the design process from a tangible portrayal of architectural design to a virtual portrayal, and vice versa. With this interchanging and crossing over of design environments from reality to virtuality the limits of each one are dismantled, both realms can be brought together in an overall process that led to alternative form findings and resulting designs. This work lies in the tradition of artists who push media to explore new interpretations both of the media themselves and of their artwork.

1. Context

Crossing over media and realms, the artist Man Ray expressed and communicated ideas in pictograms he called Rayographs (Figure 1 left; [1]) that he 'drew' directly on photographic paper using light sources. In a similar fashion, the architect Jørg Utzon and the artist Asger Jorn used virtual and real media to convey spatial expressions. Emulating a painting by Pablo Picasso, Asger Jorn used a 'light pen' and photography to re-present sketches by Utzon (Figure 1 right; [2]).



► Figure 1. Left: Rayographs 1922 by Man Ray. Right: Asger Jorn using a 'light pen' to sketch.

In the design process, architects use both physical and digital forms. The design of the Guggenheim Museum in Bilbao, for example, employed physical models that were translated into digital form (Figure 2; [3]). With the re-representation from a virtual to a physical three-dimensional (3D) model, shape and design are translated in such a way that they suit the characteristics of the subsequent media and tools and enabled the model to be handled in a manner appropriate for the tool. Previous research suggests that spatial understanding of architectural volumes is enhanced using virtual environments [4]. Yet, the quality of design and the depth of its form finding are directly linked to its representation [5]. This suggests that application of conventional and digital media will be affected by their characteristics and potentials. Consequently, if such characteristics and possibilities influence the reinterpretations that generate design information, then media interactions amplify the designer's opportunities [6]. A fluid working back and forth from digital to physical can offer opportunities not only to pre- or post-process design descriptions in each realm but also to explore new forms, understanding and interactions.

Inspired by the expressive work of Utzon and Jorn as they moved freely between different domains, we conducted a simple spatial design exercise. Architecture students were asked to develop a scheme using physical means

◀ Figure 2. Models of the Guggenheim Museum in Bilbao. From left: Physical, during digitisation, digital.

together with digital means to generate their design ideas. They engaged in cyclical interactions and reinterpretations of their designs from real to virtual and back to real. This process introduced students to a new approach of design creation and form finding [7].

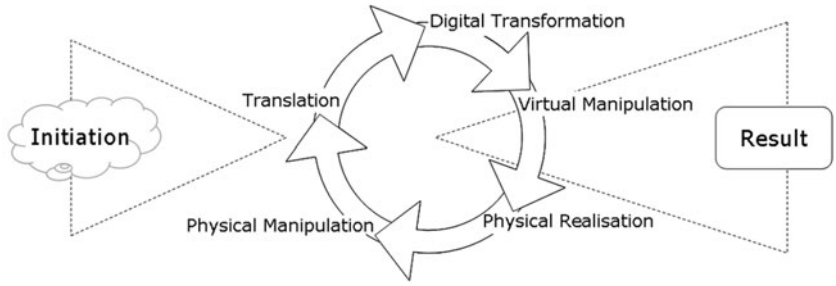
Our intention was to identify how designers translate spatial volumes and communicate design ideas by using both Virtual Environments (VE) and conventional methods of 3D depictions such as physical models. Using these outcomes, we investigated how tools for design influence the perception, comprehension and creation of spatial 3D compositions within both virtual and physical environments. We compared these results with works by artists, designers and architects, who also employed movement to express spatial compositions, to crossover a variety of realms and to create re-representations during their design process.

2. Design cycle

We engaged students in a creative process of a fictive design task that allowed a free generation and interpretation of form and space within an architectural context. There were no limitations since an important part of the whole exercise was the freedom of possibilities of each step [8]. They translated, explored and manipulated a conceptual idea within the setting of a design studio using physical and virtual tools. An idea was to be transformed from real to virtual 3D environments and back in repetitive cycles. Thirteen members of a master's course at the *Department of Architecture, The University of Hong Kong* were introduced to various tools and their potentials, details of which are listed at the end of this paper. All students had extensive prior experience using digital tools in design. After initial training and experimental exercises, the students started by using an *objet trouve* or other source of inspiration for their formal starting point. They used a 3D-scanner to translate this object into a digital 3D model by either scanning the object explicitly or, emulating Ray and Jorn (Figure 1), by moving the scanner through the air in order to 'sketch' three-dimensionally in space. The scanned file was then manipulated using a variety of modelling software, including a haptic feedback tool and the design rendered into physical 3D form using a Rapid Prototyping (RP) process for further manual transformation. The model could then be re-scanned and the cycle was repeated as the students refined their designs until they reached a

satisfactory outcome. Finally, the students presented their designs using physical models and digital projections showing the final outcome as well as the process they undertook to arrive at their result. Figure 3 illustrates the design cycle and its steps. The design cycle is described in more detail below and outcomes can be viewed online [9].

► Figure 3. Design cycle: From a mental idea to a physical result via virtual and real translations.



2.1. Initiation

The students started the cycle by choosing any object or movement as a starting point. The objets trouve chosen varied from a bottle of water, a leaf from a tree, folded paper, to parts of their own body. Some students did not choose a tangible object per se but chose instead to create a virtual object from a movement through space, scanned by moving the handheld scanner over a dynamic tracking device. This virtual 'object' described a dance, a rhythm or a path. These objects, real and virtual, provided the seed from which the cyclical design process evolved (Figure 4).

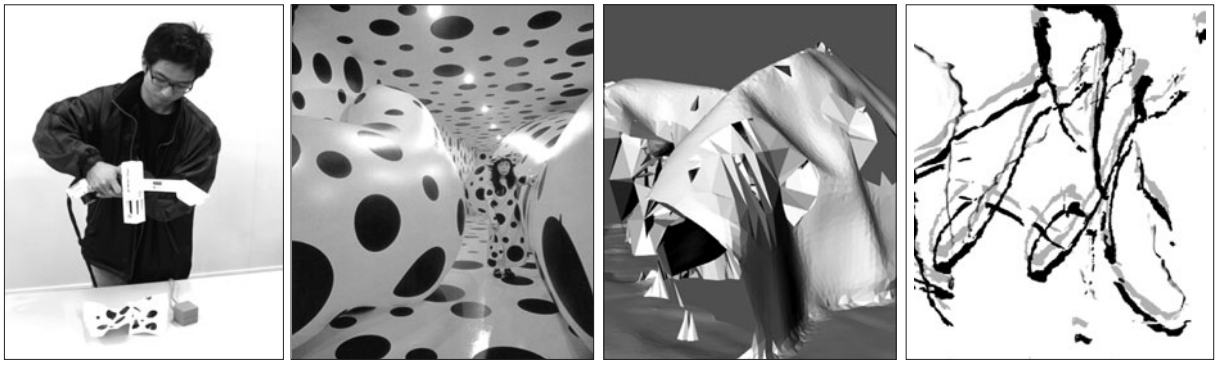
► Figure 4. Sample of objects used by the students. From left: bottle, paper, leaf, calligraphy and movement.

2.2. Translation

The object was translated into digital form by means of a 3D scanner (*Polhemus FastSCAN*). The scanning process is not a faithful replication of an object but a reinterpretation; errors and occlusions are introduced that do not exist in the physical form. Exploiting these properties, the students made use of the 'shortcomings' to create new forms. For example, the

speed of movement and the repetitive sweeping of an area affect the quality of the scan. Rather than attempting to correct the digital description to remove these accidental re-interpretations, the students used these data to mutate the 'gestalt' of the initial form [10]. For example, a technical limitation of the scanner is that dark elements of a scanned object are not recognised and are therefore omitted from the digital representation. One student, inspired by the work of the Japanese artist Yayoi Kusama who uses black dots as the key element of her art (Figure 5 middle; [11]), chose to exploit this scanning of non-objects. The student scanned folded paper with large black dots to intentionally create holes within the scan (Figure 5, left).

The scanner also can be used to record movements through space allowing users to 'sketch' three-dimensionally in space. Following the method of Asger Jorn (Figure 1 right), some students sketched their designs in the air using the 3D scanner as a 'pen' (Figure 5 right).



▼ Figure 5. From left: Scanning paper, artwork by Y Kusama, screenshots of scanned paper and movement.

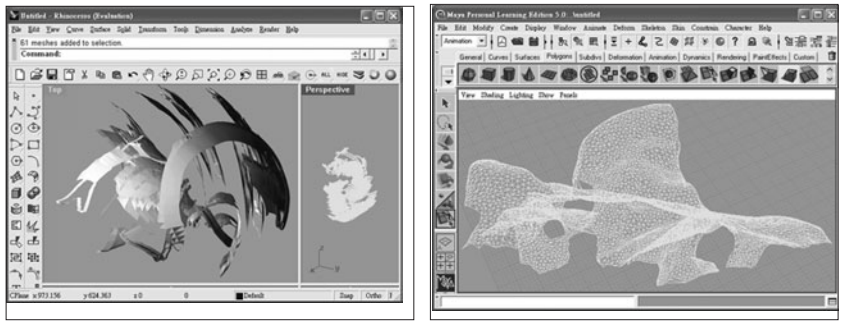
The scanner software allows users to control input sensitivity through settings for different resolutions, mesh-sizes and triangulations of the digital model. The export-function of a typical CAAD-file (such as *3ds, dxf or stl*) can manipulate the model to produce a range of different outcomes. The model can either be fragmented into several objects, or melted into a low resolution scan or a cloud of points which are either unconnected or connected by straight lines or curves. These possibilities were tools that the students could use to transform original scan into an abstract arrangement of form and space within its virtual representation.

2.3. Digital Transformation

Once a scanned element was created, it was manipulated further using digital tools. This part of the sequence of translations required some technical expertise about modelling software. Several technical problems were encountered; for example the scanning process produced a very large number of polygons and points. As a result, the file-size of the exported scan was very large, requiring substantial processing power. The students used a *Dell Precision Workstation*, which is able to handle such file-sizes and

compute such data. The 3D scanner's software exports the model as a surface rather than a solid. Since solids were needed in the next phase of the studio, most students translated the model into a solid at this stage. Additionally, some students reduced the amount of polygons, while others selected a part of the model and continued to work with their chosen selection only.

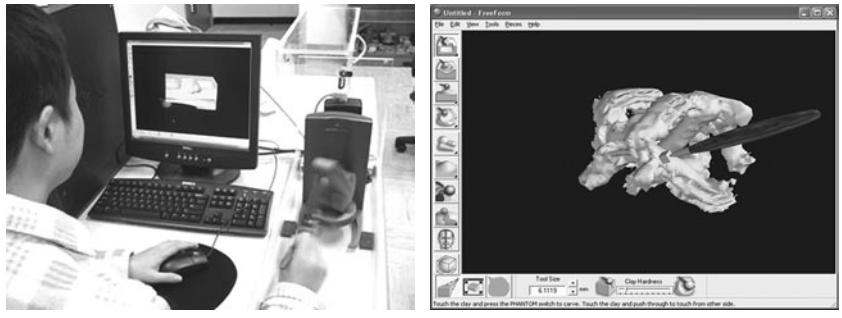
Various functions of modelling software (such as *Rhino 3D, FreeForm* or *Maya*) allow users to modify their design in expressive ways. Students investigated a range of transformation techniques to explore their designs using the standard repertoire of CAD software such as Boolean operations, volumisation, projection, extrusion, skinning, slicing as well as others (Figure 6).



► Figure 6. Screenshots of a design using modelling software. Left: Rhino 3D. Right: Maya.

2.4. Virtual Manipulation

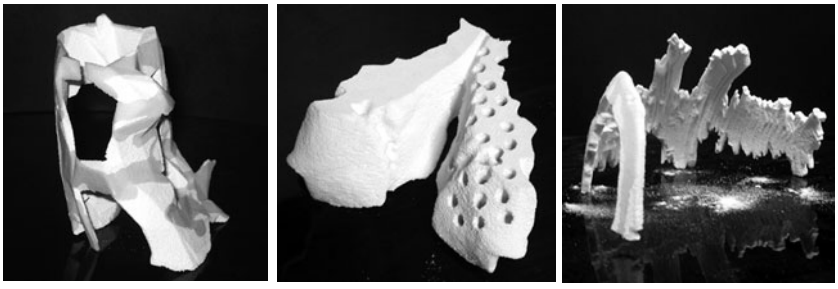
In this step, we brought together VE with reality. Our students manipulated their models by using a haptic-feedback tool (*Phantom*) to rework their digital design. The combination of the force-feedback device with the modelling software *FreeForm* allowed the students to explore their designs, merging virtuality together with physicality, the intangible with the tangible. The digital models were given the properties of physical clay. The students made changes to their design with the same ease as they would modify physical clay models by cutting, carving, sculpting, smudging and pressing elements or adding additional shapes (Figure 7).



► Figure 7. Left: Student using *Phantom*. Right: Screenshot of design using *FreeForm*

2.5. Physical Realisation

Architectural designers use physical models as a means by which to interpret their designs. The phases described above enabled the students to create and interpret their design from a physical object or movement to a design within VE. In order to materialize the model back into a physical environment, the students printed their models using a *Z402 System 3D-Printer*. With the re-presentation from a virtual to a real model, shape and design were translated in such a way that they fit into the next medium's characteristic. At this point, the physical RP-models act as the tool for communication and abstraction of the design development (Figure 8).



◀ Figure 8. Printouts using the 3D-Printer. From left: 'paper', 'leaf and 'movement'.

2.6. Physical Manipulation

Using the RP-printout, the students developed their designs with the conventional techniques of model-making. However, due to the fragility of RP-models, the potential for physical manipulation and modification is limited [12]. With some careful work, students added elements, removed other parts or divided the models into subparts (Figure 9).

◀ Figure 9. Models were altered using conventional methods of model-making.

This phase closed the circle from real to virtual and back to real. Having been through one complete cycle, the students were free to repeat any of the phases until they finished their design and assembled a final presentation.

2.7. Presentation

The students recorded and documented the development process for their designs so that they could communicate and comprehend the intention of the design as well as its outcome. They used both web-based presentations as well as all models, including the original object and all interim products. In a final review, external critics discussed and commented on the processes and outcomes of the students' work in a typical design-studio critique. This phase made it possible to evaluate and reflect on the design-circle that allowed the students to communicate the intention, the transformation and the outcome of the design to a broader audience. That gave the students to internalise and transfer their experience and knowledge to other architectural contexts. Since all students treated the above described phases in a different manner, the outcomes were of diverse. The presentations allowed the students on the one hand to understand the impact of their own actions within the process, on the other hand to learn from other students' methods and their outcomes (Figure 10).

► Figure 10. Student presenting his work during the final critique.

3. Impressions

Trained to work in either physical or digital realms, the students adapted slowly to this cyclical way of designing. Environments for designing had become correlated to specific modes of designing. Two dimensional media had, after years of training, been correlated with plan arrangements from which form are extruded or developed in section though not in volume explicity [4]. The students had been trained to design analytically, building upon functional and rational aspects of their design. In this studio however, the students were required to work entirely within a 3D environment from start to finish, developing and reflecting on their designs volumetrically and spatially.

While architects explore their designs digitally, using CAAD software, and physically through tangible media, such as clay, paper, cardboard, cutters and glue, these realms are treated separately as individual entities rather than integrated into a continuous process. We wished, however, to link directly between these domains. Each stage of the design cycle in the class

built upon the preceding step and opened up to the next; each translation offered students the opportunity to discover further and recreate their design; each medium facilitated different acts of interpretation or transformation, which again were elaborated within the next phase. At every stage, the students moved beyond their initial formal ideas in the previous phase and developed new concepts, achieving new expressions in their design. The virtual representation of their work allowed them to investigate the spatial composition in a way that they could not imagine in advance, i.e., after choosing their object in the first phase and transforming it in each following phase.

This studio successfully dismantled the boundaries between real and virtual environments to the extent that each crossed over to the other. VE can be an environment for design distinguishable from other tangible tools and yet facilitate tangible and real products. All media were used and needed to achieve a design conclusion. Based on earlier research [13] this studio focused on multiple rather than single interactions.

A significant feature of the studio was that students worked always in three dimensions, drawings were not produced. Digital and analogue media introduce new aspects to the design and are neither neutral nor transparent. Interactions in different media confront the designer with unique objects that arise from scanning and model manipulation. These artefacts force the designer to recapitulate previous interpretations of volume and space, and thus become sources for new forms. For example, at the first step the scanning, and the subsequent triangulation of the form, translated the physical model into an altered design. As Panepinto [14] points out, similar to transformations from digital to physical domains, the accuracies and settings of the scanning process offer a variety of new design elements that were not possible such as liquid conversions, facetted surfaces as well as manipulation of surface complexity or error generation as methods to reshape the physical model.

The studio brought together strands of prior research on different digital tools, allowing us to observe their interaction. Previous research suggested that spatial creations of architectural volumes are enhanced using VE [15]. Consequently, we asked the students to transform their design in VE. In this way, the design proposals could be examined in an inclusive, real-scale and three-dimensional fashion. Gibson et al. [16] suggested that RP can play a significant role in the design process that involves VE and that produces physical representations on demand. Here the students moved from VE to RP output and into digital forms again. As has been noted [12] 'RP models do not lend themselves to conversation as they are fixed in form and fragile in material'. We observed that the students could not modify their RP models following the traditional techniques of model-building yet, as with problems in earlier phases, the students adapted creatively to these problems and physical models acted as the tool for

communication and abstraction of the overall process of design.

Each of the phases is an essential part of the overall design creation and addresses only certain aspects of it. This enables a holistic dialogue about design, form, function and architectonics, which is significant not only within architectural education, but also in all other dialogues involving spatial representations. We did not expect any specific architectural design outcomes; hence it is surprising what creativity and spatial exploration of architectural forms and spaces generated in our design studio. The random starting point of the design development turned very quickly into a serious dialogue of space, form and gestalt. The initial difficulties of the students to approach design and its creation in an unusual way were overcome through the process. The students reported that this studio opened up their minds to explore architectural design in a variety of ways. Since this design-studio was experimental we did not obtain conclusive data to explain and analyse all individual phases of the studio, however the students were able to reflect and reported later that they transferred their experience and knowledge gained to other studio situations.

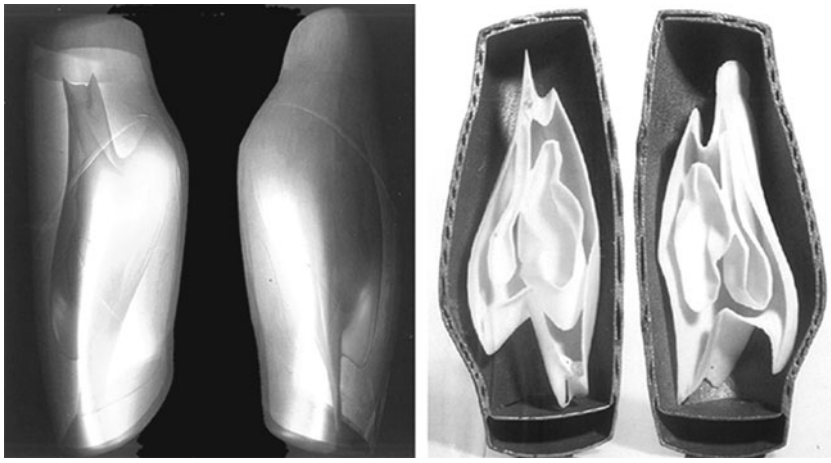
4. Crossing over

There is a gap between the imagination of a design and its representation, communication and realisation: architects use a variety of tools to bridge this gap. Digital tools are increasingly playing a role in bridging this gap yet the translation from physical to digital often poses a major barrier.

Most tools of VE are only used for presentation or simulation. Designing within VE, moving back and forth from and to reality, may minimize this divergence. This empowers designers to express, explore and convey their imagination with fewer differences. Unlike the digitisation of Frank Gehry's models that are translated as a facsimile to be rationalised and optimised for a production-process (Figure 2 middle) without further design development, the design cycle described above develops and explores the design at each stage. The cyclical nature of this studio opened up opportunities offered in the transformation from one environment to another. The designers therefore could explore different possibilities of their designs that were unique to each phase. Not only was each medium explored for its own strengths and weaknesses, but also the process of translation, such as scanning, itself became a creative act.

Design is an activity that is highly complex and influenced by numerous factors. The process may follow rules or established proceedings and traditions. Alternatively, the designer may choose to freely explore without need to heed conventions. In all instances, the medium in which the exploration takes place will affect to some degree the act of designing (similar to Jorn, Figure 1 right). For this reason, the very different nature of each design realm allows architects to create objects that make use of the properties of the design environment that the other does not offer. For

example, *OCEAN North* dismantled those boundaries and employed a similar method to our design cycle exercise by exploring different media to achieve a design. In their design for the *New York Times* time-capsule *a_drift*, the group demonstrated how layers of digital movement around given physical objects determine the capsule's unique gestalt (Figure 11 left; [17]). By using various media, the final form is refined and produced with the help of RP (Figure 11 right; [17]).



◀ Figure 11. Ocean North's time-capsule. Left: Computer-model. Right: Section through the RP-model.

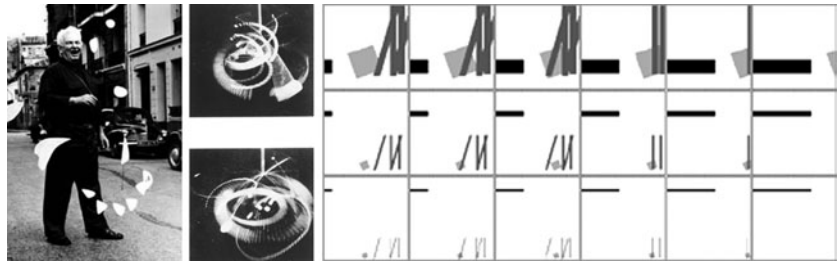
Another recent example is the *Paramorph Gateway* proposal by *dECOi Architects* [18]. The architects started with the existing base void of the site and then distorted the form not just parametrically but also paramorphically in order to achieve a gestalt of patterns and rhythms of movement of the site (Figure 12 left). They treated virtual and real components of their design not separately, but as a whole. This resulted in a design that does more than just fit function, as expressed for example in Alvar Aalto's *Paimio Sanatorium* (Figure 12 middle; [19]), or gestalt, as mentioned above in regard to Gehry's design (Figure 2).

◀ Figure 12. Left: dECOi Architects' *Paramorph Gateway*. Middle: Alvar Aalto's Paimio Sanatorium. Right: Pascal Roulin's *A-POC* line designed for the Issey Miyake Design Studio.

Similar design methods are also used in other creative processes. *The Issey Miyake Design Studio* uses digital animation to overlap material properties of a fabric with the movement of the human body. In the *A-POC* line of garments, Pascal Roulin [20] employed both real and virtual tools to

create clothing that lies outside of conventional fashion design (Figure 12 right). The design method included heat-cutting and chemical shrinking of synthetic fabrics, positioning of buttons employing digital animation and morphing of the cloth in both a virtual and real way around the body. Each step was created in a separate environment and design phase, but built upon each other to reach the final design stage of a person wearing the outfits.

Design cycles and crossing over media and domains are methods regularly reinterpreted and applied by artists. One example would be Herbert Matter's short film that he made over half a century ago on the artwork of the artist Alexander Calder (Figure 13 left; [21]). Based on cinematic techniques, he merged movements of Calder's mobiles with sound elements using John Cage's interpretation of music (Figure 13 middle; [22]). Applying this understanding of intersecting realms (shape, sound and animation), John Maeda [23] translated 2D shapes within his experimental *Parametervision*. Here, digital representations of figures constructed by a 2D parametric system can be viewed in a single image plane and at the same time understood spatially (Figure 13, right).



► Figure 13. Left: Calder with his mobile. Middle: Matter's 'animation'. Right: Maeda's *Parametervision*.

As with our design experiment, these examples illustrate how non-linear design processes and re-representation of an idea can lead to new designs and expressions that differ from conventional approaches to design. The exploration of the gestalt within both environments enhanced the understanding of spatial issues and led to meaningful and new architectural results. Despite the fact that a 2D representation of 3D space is the predominant medium through which to understand and communicate spatial arrangements, the designers' comprehension of complex volumes is enhanced by the re-representation of a 3D medium [24]. The novel aspect of this studio work was the engagement of the process of translation itself as a creative act.

5. Conclusion

Exchanging 3D tools and elements of physical and virtual environments in an experimental design studio proved to be successful. The students created, transformed and re-interpreted complex spatial designs by manipulating them within 3D space. Translation from physical to digital was

engaged not mechanically but creatively. The design process sprung not from *objets trouve* but developed from *objets digitalisé*. A series of solutions from both environments together generated understandable and rich spatial expressions. We learned from our experiment that boundaries between the physical and virtual realms can be dismantled and that these realms do not need to be treated separately as individual entities. The crossover between both domains allows a different approach towards design creation, exploration and communication.

Artists and designers have always pushed media to a new definition both of the media themselves and that of their artwork. As Man Ray (Figure 14 left; [1]) explored with his photographic method the boundaries of a medium, he arrived at new techniques that allowed a different understanding of movement and space. Also, Frank Lloyd Wright's Guggenheim Museum (Figure 14 middle) demonstrates how architectural design is not limited to a certain way in which we understand and perceive buildings in design, gestalt and function. However, it is new to use these potentials and translate them by employing current technologies. Hence, our students embarked on a new understanding and communication of architectural gestalt, form finding and design process (Figure 14 right). For example, in our case, an experimental design-studio was successfully conducted employing tools and elements of the physical and virtual environments in which the 3D scanner became a sculpting and sketching device, rather than a copying or explicit translation tool. Reality was expanded into a new dimension without being duplicated, while virtuality became its own reality that complimented the physical realm in its own right.

◀ Figure 14. Right: Rayography 1926. Middle: Guggenheim Museum New York. Right: Scan of student.

Acknowledgements

The authors would like to thank the students and the members of our Research Group of the Department of Architecture, The University of Hong Kong for participating in the design cycle and making critical comments throughout our work. Some financial resources supporting this work were made available by the Hong Kong University Grants Council.

References

1. De l'Ecotais, E., *Man Ray Rayographies*, Paris, 2002.
2. Weston, R., *Utzon – Inspiration · Vision · Architecture*, Edition Bløndal, Hellerup, 2002.

3. Bruggen, C. v., *Frank O. Gehry : Guggenheim Museum Bilbao*, Guggenheim Museum Publications, New York, 1999.

4. Schnabel, M. A., 3d Maze: Creation and Translation of Abstract Virtual Architectural Environment, in: *The 'Second Wave' of ICT in Education: From Facilitating Teaching and Learning to Engendering Education Reform, the International Conference on Computers in Education (ICCE)*, ICCE, Hong Kong, 2003, pp. 1201–1209.

5. Kvan, T., Learning through Structural Activity in Collaborative Computer Aided Design, in: Ahmad Rafi, M. E., C. W.K., N. Mai, T.-K. N. Ken and A. S. A. Sharifah Nur eds., *Seventh Conference on Computer Aided Architectural Design Research in Asia (CAADRIA)*, Prentice Hall, Multimedia University, Cyberjaya, 2002.

6. Herbert, D. M., Models, Scanners, Pencils, and CAD: Interactions between Manual and Digital Media, in: Kalisperis, L. N. and B. Kolarevic eds., *Computing in Design – Enabling, Capturing and Sharing Ideas – Conference of the Association for Computer Aided Design In Architecture (ACADIA)*, ACADIA, University of Washington (Seattle, Washington), 1995, pp. 21–34.

7. Schnabel, M. A., Kuan, S. K. S. and Li, W., 3d Transformations – 3d Scanning, Digital Modelling, Rapid Prototyping and Physical Depiction, in: Lee, H. S. and J. W. Choi eds., *Ninth International Conference on Computer Aided Architectural Design Research in Asia (CAADRIA)*, CAADRIA, Seoul, 2004, pp. 227–238.

8. Brady, D. A., Percept Vs. Precept: Digital Media & the Creative Process, in: Donath, D. ed., *Promise and Reality: State of the Art versus State of Practice in Computing for the Design and Planning Process – 20th Conference on Education in Computer Aided Architectural Design in Europe (eCAADe)*, eCAADe, Weimar, 2000, pp. 261–264.

9. Schnabel, M. A., 3d Translation, http://3d.arch.hku.hk, 2004/06/02, 2004.

10. Arnheim, R., *Visual Thinking*, University of California Press, Berkeley, CA, 1969.

11. Hoptman, L. J., Kusama, Y., Tatehata, A. and Kultermann, U., *Yayoi Kusama*, Phaidon, London, 2000.

12. Kvan, T. and Thilakaratne, R., Models in the Design Conversation: Architecture Vs Engineering, in: Clare, N., S. Kaji-O'Grady and S. Wollan eds., *Design + Research: Project Based Research in Architecture*, The Association of Architecture Schools of Australasia, Melbourne, 2003.

13. Kvan, T., Collaborative Design: What Is It?, *Automation in Construction*, 2000, 9, pp. 409–415.

14. Panepinto, B., *Revolutionary Laser Scanning for Rapid Prototyping and Reverse Engineering*, 2001.

15. Schnabel, M. A. and Kvan, T., Implementing the First Virtual Environment Design Studio, in: Tan, M. ed., *Architectural education for the Asian century – 1st ACAE Conference on Architectural Education*, Centre for Advanced Studies in Architecture, National University of Singapore, 2001, pp. 157–166.

16. Gibson, I., Kvan, T. and Ling, W. M., Rapid Prototyping of Architectural Models, *Journal of Rapid Prototyping*, 2002, 8, pp. 91–99.

17. Hensel, M., Sotamaa, K. and projects, O. N., Vigorous Environments, in: *Contemporary Techniques in Architecture* Wiley-Academy, London, England, 2002.

18. Goulthorpe, M. and dECOi Architects, Paramorph, Migayrou, F. and Centre Pompidou eds., *Architectures Non Standard : Exposition Présentée Au Centre Pompidou, Galerie Sud, 10 Décembre 2003-1er Mars 2004* Centre Pompidou, Paris, 2003, pp. 76–77.

19. Weston, R. and Aalto, A., *Alvar Aalto*, Phaidon Press, London, 1995.

20. Roulin, P., Issey Miyake Design Studio, in Rahim, A. ed., *Contemporary Processes in Architecture Wiley-Academy*, London, 2000, p. 112.

21. Calder, A., *Alexander Calder: A Retrospective Exhibition, Work from 1925 to 1974, October 26 to December 8, 1974*, Museum of Contemporary Art (Chicago Ill.), Chicago, 1974.

22. Migayrou, F., *Architectures Non Standard : Exposition Présentée Au Centre Pompidou, Galerie Sud, 10 Décembre 2003-1er Mars 2004*, Centre Pompidou, Paris, 2003.

23. Maeda, J., *Creative Code*, Thames & Hudson, London, 2004.

24. Schnabel, M. A., Collaborative Studio in a Virtual Environment, in: Kinshuk, R. Lewis, K. Akahori, R. Kemp, T. Okamoto, L. Henderson and C.-H. Lee eds., *Learning communities on the Internet – Pedagogy in implementation, Proceedings of the International Conference on Computers in Education (ICCE)*, IEEE, Auckland, 2002, pp. 337–341.

Apparatus

Dell Precision WorkStation M530 with 21" Monitor, Dell Inc., Round Rock, TX, USA, http://www.dell.com/

FreeForm Modeling System, Touch-based modelling software for Phantom, SensAble Technologies Inc., Woburn, MA, USA, http://www.sensable.com

Kaiser Proview 60. Head Mounted Display, Kaiser Electro-Optics Inc., Carlsbad, CA, USA, http://www.keo.com

Phantom 1.5/6DOF high-fidelity, 3D force-feedback device, SensAble Technologies Inc., Woburn, MA, USA, http://www.sensable.com

Polhemus FastSCAN, Handheld laser scanner for 3D scanning based on magnetic motion tracking, Polhemus, Colchester, VT, USA, http://www.polhemus.com

Z402 System, Rapid Prototyping (RP), 3D Printer, Z-Corporation, Burlington, MA, USA, http://www.zcorp.com

Marc Aurel Schnabel, Thomas Kvan, Steve K.S. Kuan and Weidong Li
The University of Hong Kong,
Department of Architecture,
Hong Kong,
China

Marcaurel@hku.hk, tkvan@hku.hk, kskuan@hkusua.hku.hk, wdli@hkusua.hku.hk