SHAPEUD: A REAL-TIME, MODIFIABLE, TANGIBLE INTERACTIVE TABLETOP SYSTEM FOR COLLABORATIVE URBAN DESIGN

by

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To my parents, for their unconditional love.

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ABSTRACT

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This research was to develop a real-time, modifiable, tangible interactive tabletop system for participatory urban design. The targeting user group was those stakeholders in urban design charrettes. Previous system solutions overlooked the importance of the modifiable tangible medium in the situation of reaching spatial-temporal consensus. These design issues impeded communication between the stakeholders and the professionals. Users of these systems had difficulties expressing ideas to professionals during the collaborative design process. Literature in evolving technology in the smart city context, collaborative urban design, embodied interaction, and depth-sensing was referred to guide the system design. Based on the review, this research identified the pivotal role of a shapeable and tangible medium in the system. The prototype system unified the modifiable, realistic model with its digital equivalent in urban analytics in real-time. By integrating tangible interaction, depth-sensing, and large touch screen tabletop, an intuitive, immersive decision-making interface for non-professional stakeholders could be created. During the system implementation, system elements centering 'tangible interoperability' were documented along the system pipeline. A heuristic evaluation, a method of usability inspection, was conducted to assess and to guide the future system design. The result was promising and inspiring. In the end, challenges and directions of system design were discussed. The contribution of this research included: discovering direction, centering tangibility, implementing a prototype, and documenting elements in each stage along the system pipeline of designing a modifiable tangible interactive tabletop system for the urban design charrette.

Keywords: tangible interaction, urban design, immersive analytics, hybrid user interface, depth-sensing, human-computer interaction

CHAPTER 1. INTRODUCTION

1.1 Background

Urban design is an interdisciplinary field that requires the cooperation of built environment professions, including architecture, landscape architecture, urban planning, and many other civil and municipal engineering (Van Assche, Beunen, Duineveld, & de Jong, 2013). Besides the buildings' design and arrangement, urban design more concerns about the quality of public spaces or public domain, such as alleys, streets and traffics, plaza, squares, and parks. Moreover, factors such as physical impacts and social impacts are bringing in other complications when the general public is sharing these spaces. There is no easy solution when the public interest is overlapping as new requirements evolve.

1.2 Statement of the Problem

Urban design is undoubtedly a complex and interdisciplinary activity and processes that involve multiple professionals and even a broader range of stakeholders at the public consultation stage. While negotiating overlapping interests, effective and efficient communication can only be achieved by the correct understanding of the current site situation by all parties in the participatory urban design. More importantly, everyone could express their design intention and conduct design exploration.

A design charrette is one of the practical approaches to foster and integrate these kinds of collaborative design. A design charrette typically features diverse groups of stakeholders jointly draft a shared vision and solution in an intensively short time. The common agenda of charrettes may be different depends on the urban issue, but the general idea of a charrette is to organize a diverse group of stakeholders that can freely collaborate in order to 'generate visions for the future' (Roggema, Martin, Remnant, Alday, & Mansfield, 2014). For example, experts from multi-disciplinary such as architects and urban designers, as well as other professionals like city planners, transportation engineers, infrastructure providers, or even city dwellers that have vested interests in it can participate in this event. Different groups can provide a specific perspective on the ongoing issue. All these people should have different appeals and judgments based on their knowledge and skillsets.

Unfortunately, urban design documents during the charrette sessions are mostly prepared by separate professionals by far. Lay people cannot understand the true intention of the experts fast enough without years' dedicated training. The non-professionals barely provide opinions that formal enough to be integrated into design development. When translating their ideas to the professionals, essential information could be lost. Reiteration and misunderstandings, which costs time and money, are unavoidable. A cooperating user interface must rise to the challenge of multi-lateral communication.

1.3 Significance

On the one hand, the urban design industry is still relying heavily on the physical model when presenting designs for its intuitiveness and tangibility. On the other hand, consumer electronics are gradually getting better and cheaper. Efforts of previous systems on leveraging both the advantages into an integrated solution that employ tangible interaction and digital analytics were constantly explored. In this way, the sensory quality of physical models was preserved while informative interaction was enhanced. Nevertheless, these systems only partially solved the gap, which kept them away from real-world usage. How to deliver information from the non-professionals to the professionals remained a major under-explored problem.

The proposed system was targeting effective and efficient communication of urban design charrette, especially within a limited time frame and non-professionally trained users' groups. The expectation for this tangible interactive system was to enable the users to operate on the same modifiable miniature models in high fidelity, to express ideas in the common proxemics, and to use common metrics to assess alternatives. The goal would be building a generic communication platform with the proper medium that can accept tangible input with high integrity and high functionality.

1.4 Research Questions

The research questions for this study were:

What were the current problems of interactive systems in the urban design charrette?

How to support aiding stakeholders in urban design charrette that allows easy communication, input, and modification of the design?

How effective was the prototype tangible interactive system on user interaction in charrette-like collaborative urban design activities?

1.5 Scope

The proposed system was intended to employ the multi-touch tabletop and depth sensor to more focus on (1) building an easy interface to operate by non-professionals to explore non-preset alternative designs (flexible, constructible tangible models), and (2) taking in data from non-professionals for real-time computational analysis.

After reviewing several previous system implementations related to the tangible interactive tabletops, several gaps were identified which would be scrutinized and discussed in the literature review chapter. To build an 'easy-to-learn, easy-to-use' interface that everyone can work on, a flexible and constructible medium of tangible objects was in the central place.

The implementation of the proposed system was assembled using commercialized components such as multi-touch tabletops which was typically used in museums, affordable red, green, blue, depth (RGB-D) sensor that was originally used in the video gaming console, and highly constructible medium, such as LEGO bricks. The main limitation of this research about the hardware and medium choices was the scene can only be constructed on a certain scale and certain modular units, but the proposed methods and principles were not confined to a specific manufacturer. Also, the software and web services used in the proposed system could be substituted with similar functionality but open-source packages.

1.6 Assumptions

The assumptions of this study were:

1. There was barely existing literature about tangible interactive tabletop that used modifiable medium specifically in the urban design charrette setting by the time this document was completed. Therefore, there was a need to explore how flexible input can be used to foster communication.
2. The chosen hardware and software were working correctly according to specified parameters, and the computing performance would suffice to conduct the study.
3. The modifiable tangible pieces used in this study, the LEGO bricks, were manufactured complying with the same standard.
4. The selected urban development project site was good enough to demonstrate the use of the proposed tangible interactive tabletop.
5. The participants had basic knowledge or understanding of buildings construction and urban environments.
6. The participants reported their experience with the usage of tangible tabletops accurately and honestly.

1.7 Limitations

The limitations of this study were:

1. While miscellaneous types of the physical objects can be used in the system, only the LEGO bricks were used in this study, which may limit the scene construction to a few selections of certain scales and modular units.
2. The touchscreen tabletop configuration was limited to perform on the Ideum platform 65-inch 4K resolution model.
3. The choice of the RGB-D sensor in this research was limited to consumer-grade with high accessibility, and therefore, resolution and precision of depth images were limited.
4. The system evaluation response was limited by subject availability, their specialty, and their previous experience of using tangible tabletops.

5. The study site of the evaluation was limited to Heavilon Hall 107 in the West Lafayette campus of Purdue University due to the bulkiness of the tabletop system configuration.

1.8 Delimitations

The delimitations of this study were:

1. This study was using compositions and combinations of hardware, software service, and tangible mediums that could be obtained off-the-shelf and sophistically commercialized in the mass market. Other experimental technologies and prototypes were not examined and included.
2. The study focused on intuitive, cooperative, and natural interactions between humans and humans, as well as between humans and the system. Wearable devices such as VR/AR goggles and other extra mobile devices that exclusive to single users were not studied in the system design.
3. A full-scale, comprehensive user experience evaluation with the real-world application was out of the scope of this study.

1.9 Definitions

digital model – computer-aided design models equivalent in the form of digital files representing the tangible input.

red, green, blue, depth (RGB-D) sensor – An imaging device that captures both color image and depth information image.

immersive analytics – an environment with virtual space to some extent shared with information visualization or analytic reasoning by multiple people.

general public – members of the public that have little professional knowledge of architecture, urban planning, and urban design.

tangible input – a smaller-scaled physical object which representing a single building or urban areas with simplified details, interchangeably used with physical input, physical model, realistic model, or ad hoc model in this paper.

touchscreen tabletop station – a computer equipped with a large horizontal screen on the top surface, which allows for touch interaction and physical object-placing purposes.

urban metrics – a set of measures or indicators of properties either in categorical or quantitative such as the terrain, climate, administrative zoning, built environment, human behavioral activity, connectivity, economics.

ICT – an abbreviation of information and communication technologies.

1.10 Summary

This chapter depicted an overall review of the research project. Statement of the problem, significance, research question, scope, assumptions, limitations, delimitations, and definition of key terms was provided to help clarify the study. The following chapter will start to review the relevant literature in the multi-disciplinary researches on embodied interaction, tangible installation with associated societal impact, and previous tangible interaction systems design.

CHAPTER 2. LITERATURE REVIEW

Viewing from a multi-disciplinary perspective on the real-world urban design practice, the information and communication technologies (ICT) provided many opportunities for participants of the urban design charrettes into a deeper understanding and discussion. Compared to previous tabletop system implementations, the key novelty of the proposed system was employing the modifiable tangible model as one of the input. The users could address their idea to others directly with the tangible model at hand by modifying it and by demonstrating the effect immediately.

This chapter focused on the literature in answering 1) why a physical model was vital in the urban charrette situation, 2) what was the appropriate approach and medium for communication, and 3) how to arrange an informative environment around the medium. The exploration of these three focus areas gave an insight into the first research question 'What were the current problems of interactive systems in the urban design charrette?' First, this chapter briefly overviewed the concept of the smart city in the context of increasing urban populations as well as the challenges and opportunities it brought in. Then, theoretical support in community design and embodied interaction of using the tangible medium to facilitate interpersonal communication were reviewed. A timeline of empirical researches and system implementation was summarized and discussed how a modifiable model, along with other ICT age tools, could play a proactive and participatory role in the urban design-related activities. The issues of previous systems were identified and summarized into seven aspects. These aspects became the starting point of the prototype system design. The last section scrutinized the key component of the system, the depth sensor, as well as the calibration methods to ensure accurate measurement. Confounding factors of using the Kinect v2 sensor were gathered, and appropriate usage and benefit of LEGO were introduced.

2.1 Road to Smart City

'World Urbanization Prospects: The 2014 Revision' from United Nations (2015) had reported that the urban population already surpassed the rural population in 2009, and the prediction was made that in the year 2050, the urban population would grow to 6.4 billion. With the prevalence of information and communications technology (ICT) especially the mobile ICT, urban dwellers generate enormous data during everyday activities and these data were collected by all kinds of sensors as well as analyzed by all fields of researchers. This change has enabled the possibilities to extract patterns from the data, utilized these data to make citizen-centered decisions wisely, allocated urban resources sustainably, and ultimately benefited the urban dwellers in all fields. The idea of an ecosystem of harnessing, processing, computing, analyzing, and integrating the data led to the concept of 'smart city'.

2.1.1 Dimensions of Smart City

To date, the concept of 'smart city' was receiving more and more attention due to the visions in taking on intricate urban problems and the availability of all sorts of large data sets for a potential solution. However, what composite a 'smart city' and what domains it applies to, remained ambiguous. There was no consensus on the smart city definition.

Albino, Berardi, and Dangelico (2015) conducted an in-depth literature review clarifying the meaning of the 'smart city' in this context. They found out the term was often interchangeably used with 'intelligent city', 'digital city', 'knowledge city', 'ubiquitous city' and so on. After summarizing over 20 versions of definitions on different focuses, they concluded that most definition was missing the 'protagonist' which were the city dwellers themselves. This opinion was closely related to the research question of this work, which was often unfortunately deemed as a strategic ideological dimension in the urban planning field. They also discovered that along the timeline, the smart city concept had evolved from ICT technical discussion to the needs of the people and the community. This trend indicated that engagement and involvement from the citizen, not the ICT alone, was now entering the smart city visions. It was best summarized the key components of a smart city as the synergies of the technology, the people (creativity, diversity, and education), and the institutions (governance and policy) (Nam and Pardo, 2011).

2.1.2 Social Ingredients of Smart City

The inference was made from the work of Neirotti, De Marco, Cagliano, Mangano, and Scorrano (2014) in that, the reason of lacking general agreement of the term was that 'smart city' had been applied to two different domains. The ‘hard’ domains included buildings, resources, and logistics, while the ‘soft’ were domains such as education, culture, and government. The key difference was whether the application of ICT played a decisive role (Albino et al., 2015). They also reviewed the state-of-the-art knowledge and technology to clarify the dimensions and elements defining a smart city. Still, there was no universal ingredient of components and benchmark for the ‘smartness’ of a city.

Ahlers, Driscoll, Löfström, Krogstie, and Wyckmans (2016) chose to understand the smart city through the lens of ‘social machines’ as it not only understood the city in technological approach, but also achieved a citizen-oriented vision, objective, and development, or ‘giving the social aspect a center stage’. They believed that to construct the future technologies of the smart city, the citizens within must become active participants. They considered the conceptualization of the ‘social machine’ was powerful and versatile enough to serve as an equivalent of the ‘smart city’.

2.2 Technology for Future Smart City

The urban planner and urban designer are now facing the pressure of adapting and incorporating disruptive technology so as not to become outdated at the exact moment when the planning and design are carried out. Among these technologies, some of them were about or already put into application within the decade and have changed the future urban planning and urban design paradigm in designing the future smart city.

2.2.1 Collecting Data from Smart Infrastructures

The internet of things (IoT) is the paradigm that objects of daily life such as household appliances, vehicles, devices, or even consumables that equipped with embedded sensors, micro-computing system, or RFID labels, so that these ‘enliven’ objects can exchange miscellaneous data via the internet. The urban IoT paradigm in the context of a smart city can help the city administrator in multiple aspects throughout the entire urban planning and urban design lifecycle including but not limited to the health of buildings, traffic and parking conditions, water consumptions, waste management, noise reduction, particle pollution monitoring, energy usage, public lighting, and many more. The IoT and the related data are invaluable assets to the urban planning and urban design field as they document first-hand raw material for studying the urban phenomenon and zero in on the urban problem.

Zanella, Bui, Castellani, Vangelista, and Zorzi (2014) in their survey paper ‘Internet of Things for Smart Cities’ mentioned that the IoT infrastructure in the smart city could promote synergies and transparency. They pointed out the IoT paradigm was favorable by local and regional administrations for the very similar reason Schaffers, Komninos, Pallot, Trousse, Nilsson, and Oliveira (2011) stated in the ‘Smart cities and the future internet: Towards cooperation frameworks for open innovation’, which is transparency, awareness, participation, and unlimited potentials.

Perera, Zaslavsky, Christen, and Georgakopoulos (2014) came up with a sensing-as-a-service model addressing the relation between smart city and the internet of things. They used the smart cities definition of Giffinger and Gudrun’s (2010), which smart city, comprising of six components, tackled with the modern cities’ challenges: smart economy, smart people, smart governance, smart mobility, smart environment, and smart living whereas the claim of Guillemin and Friess’ (2009) emphasized the ubiquitous characteristic of IoT. They also argued that the smart city top-down vision stemmed from the need of solving urban problems, better resort to the IoT technology, for the IoT was a bottom-up technological advance that would prioritize on the topic of smart city actual needs.

During their close interaction with the local urban planning municipality, Jin, Gubbi, Marusic, and Palaniswami (2014) suggested ‘a unifying information management platform’. They noticed that the data collected by IoT infrastructure were somewhat underutilized because of the data isolation in time and locations. This situation called for a comprehensive integration of urban data.

2.2.2 Processing Data by Urban Computing

Zheng, Capra, Wolfson, and Yang (2014) saw the opportunity of tackling the urban challenges with the rising of these sensing technologies and large-scale computing infrastructures from a computing science perspective. They motivated by the smart city concept and came up with a vision of ‘urban computing’, which utilizing the ‘heterogeneous data’ to solve major urban problems. In this reading, the authors formally coined the term ‘urban computing’ and claimed the urban computing framework connected unnoticeable sensing technologies in the background, with analyzing technologies on datasets, and visualization techniques with insights to create ‘win-win-win’ solutions that ultimately foster human development.

The general framework of urban computing was fusing computing science with other traditional planning fields to provide a new toolset for urban planners and urban designers. Zheng et al. (2014) listed the real-world case application of urban computing: urban planning, transportation systems, environment, urban energy consumption, social network application, economy, and public safety and security. They also elaborated on how urban computing improved the related field. In all, the power of urban computing was too strong to ignore in the technology development of constructing the smart city.

2.2.3 Decision-making Using New Visual Approaches

Innovative visual approaches have emerged and been influential for multilateral communication in urban design alongside with the continual advancement of technology. Four ‘ubiquitous mixed reality’ concepts including mobile augmented reality, web-based service solutions, interactive public screens, and multiuser design tables for urban planning were discussed (Oksman, Väätänen, & Ylikauppila, 2014) as new visual approaches to community planning. The evolution of graphical processing power has engendered the immersive technology such as virtual reality, augmented reality, and mixed reality in recent years as new forms of real-time deliverables in the fields such as architectural design, urban design, and other built environment designs. The use of VR, AR, and MR in a broader sense, facilitated the spatial understanding. Many commercially-available tools were already put into use such as ArcGIS 360 VR from Esri, which integrating their GIS platform CityEngine on untethered VR devices.

Portman, Natapov, and Fisher-Gewirtzman (2015) reviewed the use of VR technology in architecture, landscape architecture, and environmental planning disciplines in-depth with a positive result and acknowledged the new technology transformed the traditional design workflow.

2.3 Societal Impact of Emerging Technology

While the digitally-enhanced co-design space lowered the threshold for the non-experts, these digital participation technologies also impacted the professional design practice in four new qualities: crowdsourcing knowledge, design evidence, interaction, and agile design (Münster et al., 2017). The need for early academic curriculum incorporating informal data from the general public into architectural and urban design problems was also noticed and experimented (Fonseca, Valls, Redondo, & Villagrasa, 2016). To effectively enable the input from the general public, the professionals were urged to invent a universal interface. A new workflow towards an interactive, participatory process was also invented. An interactive platform such as 'Value Lab' was demonstrated in education, research, and in workshops for a collaborative scenario, or even in remote participation cases (Halatsch et al., 2007). Their work aimed at establishing a new workflow of the participatory planning process. Another group of researchers scrutinized this new progress in real-world practice, and only to find there was still much can be done from the proactive side of the planners and designers (Houghton, Miller, & Foth, 2014). Fortunately, more and more cities around the world have now developed strategies explicitly aiming at the new digital demands to catch up with this technology advances (Alizadeh, 2017).

These changes in professional fields changed the principles for public engagement in the urban design charrettes in turns. An interdisciplinary research team deployed the 'UD Co-Spaces' application during urban design charrette with a combination of many ICT (Mahyar et al., 2016). They explored the intensive usage of affordable digital tools. From the assessment of their iterations of observations and collaboration in the 'table-centered, multi-display around' setting, they synthesized a set of seven principles for new urban design charrettes. These principles were valuable guidelines for informative platforms in this digital circumstance.

A paradigm shift was happening to refocus on the placemaking people in the local community. Compared to the traditional pre-ICT age planning process, the way that placemaking adapted the space to the people in it instead of the other way around, was considered an essential complement to the traditional planning top-down process (Cilliers & Timmermans, 2014). Gamification, as an effective strategy applying gaming elements in the placemaking process of planning, were reviewed and acknowledged (Thiel, Reisinger, Röderer, & Fröhlich, 2016). These processes led to citizen participation. Evidence showed that climbing up the ladder of citizen participation could foster equality, but only by guided. New technologies empowered the urban citizens some more steps up the ladder of citizen participation according to Arnstein's theory (Arnstein, 1969).

Nonetheless, the literature neither addressed the conditions under which circumstances were likely to work and what it could achieve, nor it could foresee the informative power by ICT. A recent study, which had been tested in multiple cases, suggested a revised version of Arnstein's original ladder (Arnstein, 1969) into a 'split ladder' model (Hurlbert & Gupta, 2015). The tabletop using modifiable tangibles fitted the 'professionally guided' paradigm for some unstructured problems at the higher level of this split ladder.

Unfortunately, however, not only the web-based service solutions were claimed to have its certain shortcomings (Nuojua, Juustila, Räisänen, Kuutti, & Soudunsaari, 2008), but also the mobile AR solution barely effective in aiding design (Oksman et al., 2014). Research more focused on citizen design science mentioned that they were aware of the face-to-face debates on decision-making activities or community activities that would not be replaced by any 'high-tech' computer tools (Mueller, Lu, Chirkin, Klein, & Schmitt, 2018). In other words, physically presenting at the same venue was the key for communicative tools to be successful in such scenarios and in-depth discussions.

2.4 Cognition Benefits from Embodied Interaction

People have limited mental resources, especially working memory in short-term memory and processing capacities. The concept of 'cognitive load' was first introduced during a problem-solving study (Sweller, 1988). Nowadays, this concept is being used widely to describe and measure mental effort in cognitive psychology. The original concept of the cognitive load was differentiated between three types: intrinsic cognitive load, extraneous cognitive load (Chandler and Sweller, 1991), and germane cognitive load (Sweller, Van Merrienboer, and Paas, 1998). While the intrinsic cognitive load is determined by the inherent difficulty of the learning material itself, extraneous cognitive load can be manipulated by modifying the approach of the presentation of the material. Later discovery (Sweller et al., 1998) showed efforts on reducing the extraneous cognitive load sometimes hinder the learned skills into long term memory which eventually learns the skill, thus suggested promoting on germane cognitive load.

The most challenging part of urban design charrette was to keep everyone on the same page in a complex context. The difficulties came from the individual differences in cognitive load capacity could vary largely (Murphy and Wright, 1984). For example, experts in a specific field have far less cognitive load than the layperson does in the same process of performing professional tasks. Therefore, designing an interactive platform that engaging people with different processing capacities proved to be complicated. Even worse, in the topic of urban design, the information could be easily overloaded by the spatial-temporal problems, the complex interdisciplinary systems, and the new technologies deployments. All these factors have left not that many cognitive resources to spend.

Embodied cognition was brought to the attention in the research of cognitive psychology and social science in recent years, which included the topic of decision-making and social interaction. Embodied cognition theories believed that our motor system, in other words, our bodily state has a strong influence on our cognition (Lakoff & Johnson, 1980). This groundbreaking finding gained momentum in academia in the 1990s. Evidence was collected that people used their previous understanding of the already familiar physical objects, position, actions to understand a more complicated concept in other new domains by using a metaphor (Lakoff & Johnson, 1980).

Study of embodied cognition showed that the embodiment such as embodied interaction had better results in the abilities such as memory (Scott, Harris, & Rothe, 2001), visual search (Bekkering & Neggers, 2002), distance perception (Balcetis & Dunning, 2007), visual perspective (Tversky & Hard, 2009), and language comprehension (Borghi & Cimatti, 2010). A recent study of retention performance, cognitive load, and motivation measures on tangible user interfaces (Skulmowski, Pradel, Kühnert, Brunnett, & Rey, 2016) also suggested that there were potential advantages that embodied interaction would not occupy traditional defined cognitive load.

In light of this statement, the universally familiar objects such as toy building blocks, LEGO bricks in the proposed system, which could be easily built into high fidelity miniature of the real world, were a suitable interface for everyone. According to this theory, the embodied interaction such as operating and modifying the modularized units could make use of the body sensory engagements and could gain deeper understandings. The proposed tangible system made use of this theory to mitigate the differences in cognitive load capacity.

2.5 Positioning the System in the Reality-Virtuality Continuum

Many kinds of system implementation could fulfill the task of re-creating the scene, showing data informatics, and relieving the cognitive workload. To determine which configuration that an interactive system should use for a participatory process, we need to consider different types of presentation and their corresponding advantages, disadvantages, and limitation. Milgram, Takemura, Utsumi, and Kishino (1995) proposed the taxonomy of mixed reality (MR) in which real objects and virtual objects were juxtaposed or overlaid based on the composition of the environment. This classification was generally accepted in the field of computer science.

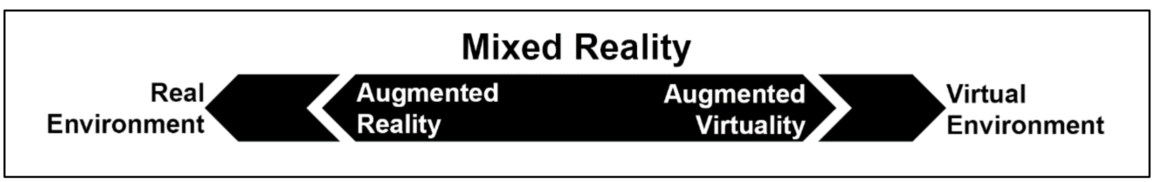


Figure 2.1 The Reality-Virtuality Continuum (adapted from Milgram, Takemura, Utsumi, and Kishino, 1995)

The 'Reality-Virtuality Continuum' is illustrated as figure 2.1, from left, where real environment with solely real physical objects presented, to the right, where virtual environment in which all the visual elements are synthetic, computer-generated.

The proposed system was intended to create a tangible-oriented atmosphere using shared objects and a shared space. It was best situated between reality and augmented reality in this 'mixed reality continuum' to the left. The tangibility was adding a layer of interoperability between all the participating parties involved in the charrette or charrette-like activity at the same physical interactive location.

2.6 Designing a System for Multiple Engagers

The study of proxemics cast light on designing the interpersonal behaviors and spaces such as nonverbal communication and social interaction, as well as how a system should respond. Also, a recent study (Memarovic, Gehring, and Fischer, 2015) has evolved the user engagement model including interactive public displays and media facades from its original context (Hall, 1963).

However, the empirical study showed the tangible interactive systems with physical installation presented, had different engagement models and dynamics from those simply with public vertically hanged displays. Challenges had been touched upon in several aspects such as mapping feedback to individuals, orchestrating group interactions, and social embarrassment and awkwardness (Vermeulen, Luyten, Coninx, and Marquardt, 2014). Much remained under-explored in this new set of interactions.

2.7 Previous Tangible System Designs

Tangible installation as a vehicle in spreading out performative interactions in the community was explored to address the ‘low engagement’ problem. It provided enough affordance and novel elements to evoke additional motivations, to activate the participation, and to make common memories for the community. Field researches had shown that dedicated tangible installations in public should be established in the early stage of planning/design to gain more attention and to start a conversation (Häkkilä, Koskenranta, Posti, & He, 2014). This kind of novel interaction successfully attracted the dwellers in the community and engaged passers-by, which potentially an effective approach to involve more people in the urban participatory design. An experiment utilizing the honeypot effect (Brignull & Rogers, 2003) in the community revealed that tangible elements could help to attract attention (Steinberger, Foth, & Alt, 2014). The action of local dwellers using the tool itself, became a performative interaction, and other passers-by could see this in the public space, and ultimately enticed more participators. Another tangible interactive urban informatics installation was a great example showing similar results (Claes & Moere, 2015), in which the mixed media (physical and digital co-exist) played an important role in transforming the one-directional, passive acceptance of broadcasting into an active engagement of placemaking.

A timeline of system implementations had been reviewed related to the tangible interactive tabletops, and gaps were identified about the problem. The previous implementation of tangible interactive tabletops specialized for aiding urban design could be organized into a chronological order based on the intensity of the tangible medium usage. Unanimously, the previous systems involved one or more flat displays (or projectors). The key difference among them was what kind of tangible media they used and how the tangible media was used. As shown in figure 2.2, the role of the tangible medium evolved as the sensing technology advanced. From the early ages of using the tangible object as a query controller, to as an urban element token, to as assignable coordinates, finally to volume-aware object, it was clear there was a trend that the tangible object gradually became a centerpiece of the system. With much more concrete the shape, users had lesser difficulties understanding the situation on the tabletop.

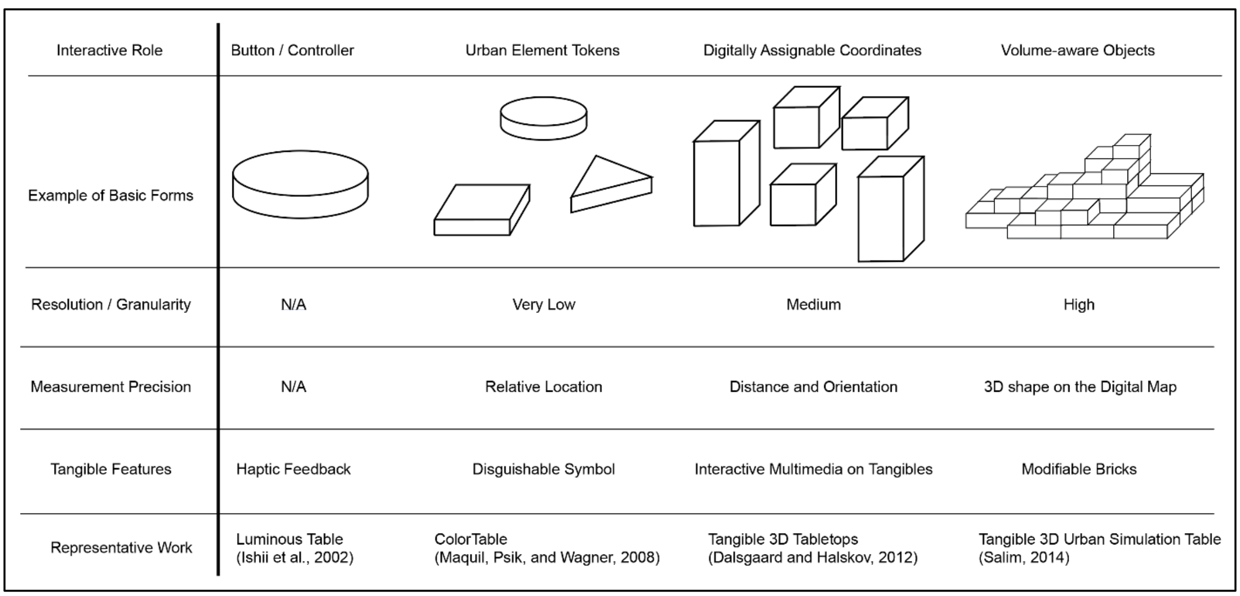


Figure 2.2 The evolution of tangible medium on the interactive tabletops. From left to right, tangible objects become more and more refined and customizable - the role of the tangible objects transformed from preset presentation to idea creation.

2.7.1 Tangible Objects as Query Controller

Earlier implementation of tangible interaction was mostly limited to some simple mapping from the tangible physical object to the virtual environment for information query purposes due to insufficient computing power. These systems had some features in common. Since the predefined tangible objects were no longer modifiable once they were registered in the system or placed on the tabletop, these implementations could be considered the augmented or volumetric (extruded) version of the 2D solutions. While the user could move the tangible objects across the tabletop, the interaction of the objects itself was highly limited. The only meaningful interaction that a user could change was the locations and angles of the rigid model within the predefined site in this kind of system. The Luminous Table (Ishii et al., 2002) established the earliest concept and working prototype in searching for ‘a compatible form of representation’.

‘The city at hand: media installations as urban information systems’ (Haring et al., 2010) was another example of this kind of urban informatics system. Coupling with the tangible interface and interactive information of urban data, the two installations in their system both start from everyday objects such as a knob, pen, or paper map to engage the system. The installation was a successful, informative platform, yet they also identified the pitfalls of their system. The most noticeable one was no visual reference or feedback on the table which the user was working on, and this hindered the interactive flow. The user was required to continually check and figure out the mapping relationship between the tangible movement and the information screen.

An AR framework (Graf, Santos, and Stork, 2010) for the interpretation of simulation and scientific visualization within the urban planning context was implemented. The tangible system featured a physical interactive pen to define the boundary condition or tensor field section of scientific visualization in urban physics such as meteorological conditions, wind environments, topography, or air pollution. Two optical trackers kept track of the pen location while the head-mounted see-through display provided visualization at the location where the pen was pointing. The urban district digital model was already built in the system, and the physical models were prepared beforehand for the trackers to locate the relative location with the pen probe.

While this configuration had no direct interaction with the model and the urban setting was lack of flexibility in switching, this framework was demonstrating a tangible interface for querying urban informatics on-demand in quasi-real-time.

2.7.2 Tangible Objects as Urban Element Token

In the work of 'ColorTable' (Maquil, Psik, and Wagner, 2008), a system developed following the 'design-evaluation-feedback-redesign' procedure had been made. Their focus was on how to make use of multimedia materials in a mixed reality environment to make design decisions. Different measures were used to reduce the barriers for the general public, such as color-coded blocks in different geometric shapes to represent an urban element. A barcode reader was introduced for picking up the 3D scene to assign it to the 2D colored objects. The use of a rotating table, projector, and many other valuable attempts were made to include more participators. However, due to the precision of this collaborative system, the decisions that came from this system were highly limited to an abstract structural relationship rather than location information. Later, a much larger scale experiment 'MR Tent' (Wagner et al., 2009) using the ColorTable targeted on the inhabitant of the urban development project in a real-world context was set up to attract the residents of a community.

2.7.3 Tangible Objects as Assignable Coordinates

As the tracking technology and technique accumulated, tangible 3D tabletop (Aldawood et al., 2015; Dalsgaard and Halskov, 2012) using multiple cameras and projectors was realized. The system presented a novel interface that consisted of a translucent table surface, one projector underneath the table to show contents on the tabletop surface and one camera underneath to capture input, and two projectors mounted above the tabletop in two diagonal directions. On the top of the tabletop, tangible media, or token objects which they referred to as 'tangibles', were used to control the input of users. The 'tangibles' themselves were made of white blocks and were assignable according to the locations and orientations, as well as the projections from above. The orientations of the bottom shape of the 'tangibles' were captured by the camera beneath. In their demonstration, the 'tangibles' were regular shapes such as cubic, cylindrical, or spherical, which reduced the tangible media to a token. However, the use of multiple projectors, on the other hand significantly decreased the occlusion of the projections, which made the simultaneous multiple-user scenario possible. Not only projected onto the tabletop surface, but the projectors on top also generated images or visualization on the side surfaces of the models. This design gave an extra mapping dimension to the interactive interface. They also demonstrated several scenarios in integrating maps or geodata. The urban planning usage of the tabletop did showcase the intuitive and versatile capacity for all the participants. However, for a real urban planning and urban design working environment, the set-up was still too coarse and not designed to detect height or any volumetric information about the physical model.

2.7.4 Tangible Objects as Volume-aware Object

As consumer-grade depth sensor became more and more accessible and popular, interactive tabletops with volume-aware tangibles finally came to life. A sandbox tabletop system (Petrasova, Harmon, Petras, and Mitasova, 2014) utilized the Kinect depth sensor and projector to generate an analysis of landscape with geospatial modeling. The application in terrain, hydrology, or wildfire modeling based on the digital elevation model (DEM) was highly efficient. The system was not directly targeting building block features, but the nature of depth-sensing gave a clue to a more versatile application of tangible inputs such as carved mode, or model combined with molded sand.

The tangible 3D urban simulation table (Salim, 2014) introduced the depth sensor to detect physical models into the system. The system used a Microsoft Kinect camera to capture the forms and a projector above the table. The system could then visualize wind flow patterns changes as the user changed the physical model in an urban setting.

While the set-up of the system cannot entirely eliminate the occlusion problem because of the use of projector from the top, the depth-sensing technology was first used in the physical models in an urban design setting. Once the positioning operation of the physical model was done, the wind flow simulation would update accordingly on the street level. While the Kinect depth sensor was used, yet no building height information from the tangible elements was taken into consideration when generating this simulation, as a 2D wind simulation was the only fast enough real-time computation can be achieved at that moment in the study.

2.7.5 Other than Tangible Objects

While in parallel, there were some ‘zero tangibles (pure digital, no tangibles)’ solutions using only one or multiple touchscreens and screen wall such as ‘Value Lab’ (Halatsch et al., 2007), ‘BIM table’ (Lin, Liu, Tsai, & Kang, 2014), and ‘UD Co-Spaces’ (Mahyar et al., 2016) to fulfill urban design related tasks. The ‘Value Lab’ solution utilized two tabletop screens and three on-wall display for their solution addressing the need for collaborative design in a more innovative interactive approach. However, the value lab was more of a demonstration and discussion tool which required much preparation beforehand than a productive tool for design and planning. The ‘BIM table’ (Lin et al., 2014) proposed a multi-screen solution with a public ‘BIM table’ in place and a private handheld device for each participator. The idea depicted the potentials of recognizing images from the ‘main’ public interactive table and then generating user-specific contents onto each user’s additional device.

Among them, the UD Co-Spaces (Mahyar et al., 2016) solution shared the closest goal with the proposed system. The third iteration of ‘UD Co-Spaces’ separated the design space, 3D representation, and the result of urban visualization indicators onto three different screens. The central touch table served as the main design space to engage, on-wall projection as a 3D representation of the site, and personal tablet as a query control panel, respectively. This multi-screen setting strategy engaged as many participators as possible while making the consequences more legible to the co-users.

While technically, it was still possible for professionals to update the model on-site according to the users’ verbal opinions, the understanding of the design was weakening during the process. These ‘pure digital’ solutions limited the non-professional users from changing the model by themselves. While the total digital solutions were suitable for demonstrating and comparing cases, the tangible platforms, together with pixelated, reusable, constructible tangibles such as LEGO bricks, were concerning more on prototyping and co-designing in precise details.

2.8 Depth-sensing and Calibration

A depth sensor was used to monitor the users’ interaction with the physical setting on the tabletop so that the system could recognize and track the changing shape of the tangible objects. This session reviewed the existing technology of depth-sensing cameras that were mass-produced, open application programming interface (API) available, and much affordable than specialized professional imaging hardware. Mainstream calibration methods of the depth-sensing camera in order to improve measurement accuracy were also reviewed. Since many of the APIs of first-generation Kinect camera were depreciated, the review was more focus on the second generation.

The proposed system captured the tangible shape from the user and translated the input into a digital form for further analysis. To realize this operation from physical to digital, a depth-sensing camera was used. The depth-sensing camera served as the eyes of the system. The system used a camera to measure the true world correctly to generate a trustworthy simulation before urban charrette participants could start a meaningful and productive discussion. This gave rise to the problem of camera calibration.

To understand the source of the measuring errors, distortions, the geometric calibration methods, and to choose proper depth calibration method and process, some basic notions such as the concepts of pinhole camera model, camera projection matrix, lens distortion, as well as two types of depth-sensing principles were reviewed as follows.

2.8.1 The Ideal Pinhole Camera Model

The ideal pinhole camera model abstracts the geometric relationship between the points in the 3D world coordinate system and the 2D projection on the image plane. The pinhole aperture of this model is considered infinitely small, letting all light rays between the 3D points and the 2D image pixels passing through this hole while ideally no blurring is happened due to the small size of the hole. No geometric distortion or unfocused blurring is included in this linear model.

2.8.2 Introducing Lens Together with Distortion

For letting more light passing through the hole in the same amount of time (which implies faster imaging), and other consideration such as reducing the diffraction effect of the pinhole camera (which implies clearer image), as well as shorten the light ray path towards the focal point (which implies smaller camera body), the lens was introduced into practical usage. All the parallel rays converge to a point on a plane with specific distance depending on the optical characteristic of the lens. The distance between the center plane of the lens and the focal point is denoted as the focal length f.

The introduction of the lenses also brought in the lens distortion which is an optic phenomenon that the geometries deviate from the actual proportioned shape causing noticeable aberration known as radial distortion and tangential distortion. This means the straight line on the physical model is no longer a straight line in the image, and more often than not, the same length in the real world looks shorter on the verge of the image. However, the lens distortion could be modeled by non-linear intrinsic parameters, which later facilitated the calibration process.

2.8.3 Depth-sensing beyond Gaming

There were various consumer-grade depth sensors available such as Orbbec Astra Pro, Intel RealSense ZR300 marketed by Creative, Occipital Structure Sensor, and Microsoft Kinect v2 camera. The most famous and well-supported one was the Kinect camera from Microsoft. The RGB-D camera such as Kinect was originally designed as a contactless interactive component for body or face tracking, or a gesture or pose recognizing device in the Microsoft XBOX video gaming console system. For entertainment in capturing poses and gestures, the geometric fidelity was precise enough. The cost compared to laser scanners, the portability of the combination of 3D and color information, made it a favorable choice in the robotic field (Lachat, Macher, Landes, and Grussenmeyer, 2015). For example, the Kinect v2 camera was found widely used in many fields other than the gaming industry such as inspecting luggage size in the airport recently (Anderson, 2019).

Due to the manufacturing error, the real center (principal point) and other optical parameters of the lenses were not identical for each piece from batch to batch. Still, all of them were still within an acceptable range after all. The in-factory calibration in the firmware had already implemented for these errors. Nevertheless, the need for higher geometric fidelity raised when more and more researchers attempted to exploit the potentials of these low-cost consumer-grade RGB-D camera from a casual entertainment appliance into serious professional tools for precise measurement. The manufacturer in-factory calibrated parameters, in this case, were not accurate enough to address this hardware-wise individual difference of deviations. So, this need led to more advanced calibration techniques specifically to the consumer-grade hardware.

2.8.4 Camera Model and Parameters

To determine the actual location of a certain point and to measure the actual distance between points in the real-world scene, the camera model must be set up, and the camera parameters are parameterized into predictors for estimation. After that, using several reference point pairs between the positions in the 3D world and pixel locations on the 2D image plane, the fitting of the model predictors can be performed.

2.8.4.1 Decomposition of Camera Parameters

By using the homogeneous coordinates, the projection process can be rewritten into a linear mapping. The projection matrix (also called camera matrix) P is used to map 3D points $[x_w, y_w, z_w, 1]^T$ in the world coordinates to 2D points $[u_c, v_c, 1]^T$ in camera pixel coordinates. This matrix can be represented by intrinsic matrix K and extrinsic matrix $[R|\boldsymbol{t}]$,

$$P = K[R|\boldsymbol{t}]$$

The estimation of the lens distortion parameters is not included in this model and often considered a pre-calibration process (Prescott and McLean, 1997; Swaminathan and Nayar, 1999). The separation between the lens distortion parameters from others will keep the camera model simple and thus facilitates the estimation task. The extrinsic matrix describes the rigid transformation from the world 3D coordinates to camera space 3D coordinates, while the intrinsic matrix describes the projection transformation from the camera 3D coordinates to image plane 2D coordinates.

2.8.4.2 Intrinsic Parameters

The intrinsic matrix was parameterized by Hartley and Zisserman (2004) as K being the camera intrinsic matrix such that K could be decomposed into three basic 2D transformations as follows,

$$K = M_{translate} M_{scale} M_{shear} = \begin{bmatrix} 1 & 0 & x_0 \\ 0 & 1 & y_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f_x & 0 & 0 \\ 0 & f_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & s/f_x & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} f_x & s & x_0 \\ 0 & f_y & y_0 \\ 0 & 0 & 1 \end{bmatrix}$$

The 2D shear transformation occasionally occurs for some digitization process of the acquired signals parameterized by axis skewness coefficient s between the x and the y axis shear distortion. The 2D scaling transformation is defined by the focal length f , which is the distance from the pinhole to the image plane. The scale factors m_x and m_y in terms of pixels where $f_x = m_x \cdot f$ and $f_y = m_y \cdot f$, and more than often $m_x = m_y$. What follows is a 2D translation of principal point offset x_0 and y_0, which is typically the center of the image plane.

2.8.4.3 Non-linear Intrinsic Parameters

Non-linear intrinsic parameters, including the lens distortion, are not included in the pinhole camera model because the pinhole camera does not have aberrations compared with those with a lens. To get the correct pixel coordinates u and v, the acquired distorted $\hat{\boldsymbol{q}} = (\hat{u}, \hat{v})$ coordinates need to be inverted by a distortion model.

The anti-distortion model known as the Heikkila model (Heikkila and Silven, 1997), a great extension of the original 'Brown model' (Brown, 1966), is suitable to correct distortions for most types of the optic camera system. The method is given for computing the parameters as:

$$\begin{bmatrix} u_c \\ v_c \end{bmatrix} = \Psi^{-1}(\hat{\boldsymbol{q}}) = \begin{bmatrix} \hat{u}(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) + 2d_1\hat{v} + d_2(r^2 + 2\hat{u}^2) \\ \hat{v}(1 + k_1 r^2 + k_2 r^4 + k_3 r^6) + 2d_2\hat{u} + d_1(r^2 + 2\hat{v}^2) \end{bmatrix}$$

where $r = \sqrt{(\hat{u} - x_0)^2 + (\hat{v} - y_0)^2}$, and parameters k_i with $i = 1,2,3$ are constants that responsible for radial distortion and d_i with $i = 1,2$ for tangential distortion. Ψ denotes the distortion transformation function. Thus,Ψ^{-1} is the inverse function to calculate the correct pixel location u_c and v_c.

2.8.4.4 Extrinsic Parameters

The extrinsic matrix $[R|\boldsymbol{t}]$ can also be decomposed into 3D rotation matrix R followed by 3D translation $\boldsymbol{t}$ as the transformation from the world coordinates to camera coordinates.

The 3D rotation matrix R can be further written as $R(\alpha, \beta, \gamma)$,

$$R(\alpha, \beta, \gamma) = R_z(\alpha) R_y(\beta) R_x(\gamma)$$

$$= \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma \\ 0 & \sin\gamma & \cos\gamma \end{bmatrix}$$

Thus, the extrinsic matrix can also be written as

$$[R|\boldsymbol{t}] = [I|\boldsymbol{t}]\begin{bmatrix} R & 0 \\ 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} \cos\alpha\cos\beta & \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma & \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma & t_x \\ \sin\alpha\cos\beta & \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma & t_y \\ -\sin\beta & \cos\beta\sin\gamma & \cos\beta\cos\gamma & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where α, β, γ are the rotation angles with respect to the z axis, y axis, and x axis. Notice that the order performing the rotation is not commutable and start from x axis, y axis, and then z axis, followed by the 3D translation of t_x, t_y, and t_z.

2.8.5 The Principles of Depth-sensing

2.8.5.1 Structured Light Depth-sensing

The principle of depth-sensing for the structured light type is shown in figure 2.3. The pixel-shifted distance between the measuring object and the background is called disparity. The light pattern (also called speckle pattern) is projected by the infrared projector on an in-factory predefined plane for future reference, which is stored in the sensor firmware. Another pattern is projected onto the objects to be measured. By comparing both patterns, the depth sensor can calculate the depth of the objects to be measured.

More specifically, the system projects a pattern from location $q_{i_{projector}}$ toward the predefined reference plane which the vertical distance in-betweens is Z_0, and then a different pattern on the feature point Q_i. The two different patterns are captured by the IR camera at $q_{0_{camera}}$ location that reflected from the reference plane and at $q_{i_{camera}}$ location on the image plane that reflected from the feature point Q_i respectively. By similar triangles, the following relationship holds:

$$q_{0_{camera}} = q_{i_{projector}} + f \cdot w \,/\, Z_0$$

where w is the baseline distance between the IR camera and the IR projector, f is the focal length of both IR camera and the IR projector, and Z_0 is the distance between the predefined reference plane and the depth sensor.

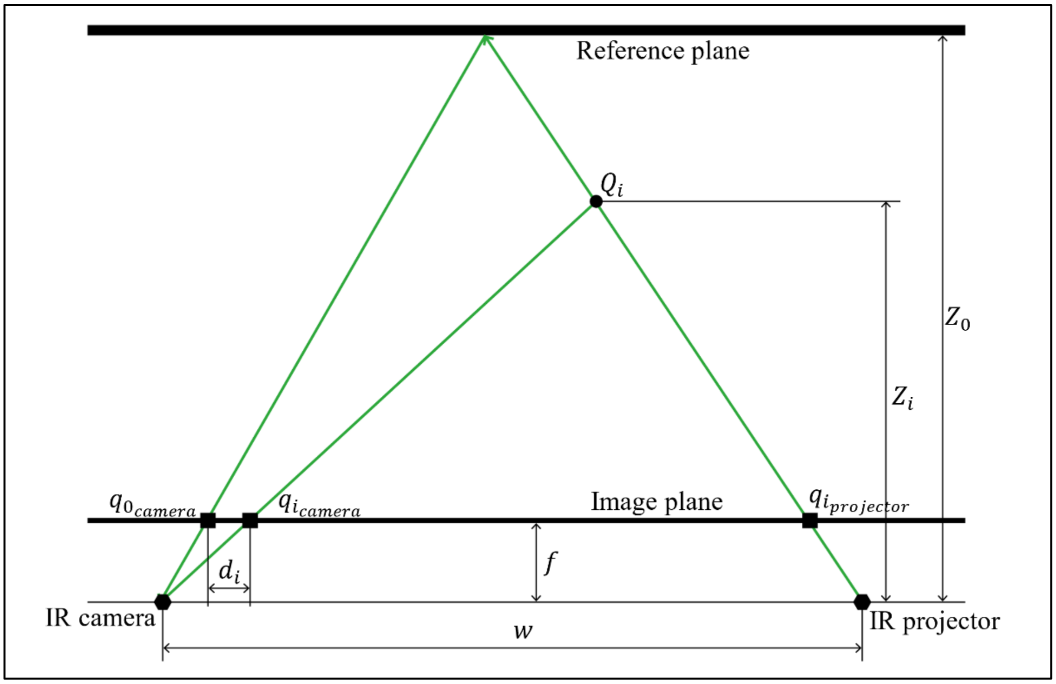


Figure 2.3 Depth measurement of the structured light type depth sensor. (adapted from Yamazoe, Habe, Mitsugami, and Yagi, 2012)

For the next step, the IR camera can capture a different pattern created by feature point Q_i of location $q_{i_{camera}}$ on the image plane. By comparing the two patterns, the system can calculate the disparity d_i for the observation $q_{i_{camera}}$ as follows:

$$d_i = q_{i_{camera}} - q_{0_{camera}} = q_{i_{camera}} - q_{i_{projector}} - f \cdot w \,/\, Z_0$$

Therefore, the 3D position of the feature point Q_i can be represented by

$$Q_i = \left[\frac{q_{i_{camera(x)}} \cdot Z_i}{f}, \frac{q_{i_{camera(y)}} \cdot Z_i}{f}, \frac{f \cdot w}{f \cdot w / Z_0 + d_i} \right]^T$$

However, the manufacturer of SL sensors normally only gave out the normalized depth value d_i' which is a linear transformation of the disparity such that

$$d_i = m \cdot d_i' + n$$

Therefore, the measured depth of feature point Z_i can be written as

$$Z_i = \frac{f \cdot w}{f \cdot w/Z_0 + m \cdot d_i' + n} = \frac{f \cdot w}{\alpha d_i' + \beta}$$

where $\alpha = m, \beta = f \cdot w/Z_0 + n$

For the error model, general approaches of systematic error and distortion error applied either Zhang's model (2000) or Heikkila model (Heikkila and Silven, 1997) could be found in practical usages. Studies such as Yamazoe, Habe, Mitsugami, and Yagi (2012) and Darwish, Tang, Li, and Chen (2017) integrated both systematic error and distortion error in addressing the error model for the structured light type sensors.

2.8.5.2 Time-of-flight Depth-sensing

Unlike the first generation of Kinect system which uses structured light (also known as active triangulation systems), the second generation of the Kinect sensor with ToF is capable of detecting objects in farther range and can have smaller hardware module size.

Two mainstream types of time-of-flight (ToF) depth-sensing technologies are available on the market, the pulsed signal, and the continuous wave (CW). By emitting modulated light signals and by measuring the phase of the modulation envelope of the light, the depth can be measured. ToF sensors have advantages over other types of depth sensors such as triangulation-based methods in less post-processing, no requirement on a baseline between its optical components, or any sensitive alignment, and no need to employ high power and high-density light sources (Gokturk, Yalcin, and Bamji, 2004).

Microsoft released the Kinect v2 depth sensor and its software development kits (SDK) for Windows in September 2014. The Kinect v2 is a CW type ToF camera with a resolution of 1920 by 1080 pixels for the RGB (color) camera and a resolution of 512 by 424 pixels for the IR camera. Both cameras are capable of capturing images for a frequency of 30Hz. By evaluating the single Kinect v2 sensor and multi-Kinect trilateration approach, Yang, Zhang, Dong, Alelaiwi, and El Saddik (2015) claimed that the Kinect 2 sensor showed potentials in fields like entertainment, education and medicine areas. Another analysis report created by Breuer, Bodensteiner, and Arens (2014) underpinned this finding and concluded that the capability of resolving fine structures compensated the resolution drop. This finding greatly extended the usage of the Kinect v2 sensor to conduct 3D model reconstruction.

Barzaghi and Pinto (2014) modeled the depth measurement of ToF camera such as Kinect v2 based on the phase-shift principle as:

$$Z = \frac{n}{2}\frac{c}{f_{mod}} + \frac{\phi}{4\pi} \cdot \frac{c}{f_{mod}}$$

where c represents the speed of light in air, n is the number of phase cycles, Z is the measured distance, f_{mod} is the modulation frequency of the emitted signal and theta is the measured phase of the returning signal. The error model can then be described as a systematic error:

$$dZ = \frac{-Z}{f_{mod}} df_{mod} + \frac{Z}{2n\pi + \phi} d\phi$$

Pagliari and Pinto (2015) commented on this modeling on the missing residual error term and considered it a second-order error thus trivial enough to ignore.

2.8.6 Methods, Procedures, and Tools for RGB-D Camera Calibration

Camera calibration, also called camera re-sectioning, is the process of estimating the camera intrinsic and extrinsic parameters (especially for the intrinsic parameter in general cases) which generally based on the pinhole camera model. By retrieving the parameters for a particular camera, the true distance of the segment can be compensated and measured from the image. The most used calibration methods assuming the pinhole camera model is Zhang's method (2000). In this method, the homography calibration process with a 2D metric checkerboard was used to provide ground truth reference point at the checker grid corners. The well-implemented and widely used tools nowadays are 'camera calibration toolbox for MATLAB' (Bouguet, 2000) and tools from the OpenCV library.

2.8.6.1 Geometric Calibration Problem

The problem of the camera geometric calibration is widely accepted as below.

Given a number N of points pairs, Q_i in world points (ground truth reference), and corresponding q_i with known pixel locations on the image plane, the task is to estimate the parameters in the projection matrix P, that minimize the error E, which the error model can be described as:

$$E = \sum_{i=1}^{N} \|PQ_i - q_i\|^2$$

Therefore, the complete goal of the geometric calibration is to retrieve the intrinsic parameters $[f, m_x, m_y, x_0, y_0]$ in linear model, the non-linear parameters $[\ k_1,\ k_2,\ k_3,\ d_1,\ d_2]$ in the distortion model, as well as estimating the rotation angles α, β, γ and the translation distances t_x, t_y, t_z according to the assigned world coordinates in the extrinsic model.

The calibration of the extrinsic parameters is straightforward as it is an explicit rigid transformation from world 3D coordinates to camera 3D coordinates. The term ‘camera calibration’ is limited to intrinsic parameters only in most of the literature for this reason. Moreover, in the proposed system, the camera and tabletop setup such as position and rotation were static, known, and fully adjustable and controllable. Hence, the camera calibration process will be more focused on intrinsic parameters.

2.8.6.2 Bundle Adjustment for Geometric Calibration

Other 3D reconstruction methods adopted the nonlinear least-squares algorithm known as bundle adjustment (Triggs, McLauchlan, Hartley, and Fitzgibbon, 1999) were also popular. These methods were mostly used for multiple viewpoints that encompass 3D coordinates of the geometry, the relative motion parameters, and the optical characteristics of the multiple cameras at the same time.

2.8.6.3 Depth Calibration Method for ToF Sensors

In principle, the ToF depth-sensing camera such as the second generation of Kinect can be geometrically calibrated as regular lens camera, as Hansard, Horaud, Amat, and Evangelidis

(2014) demonstrated in their work. While retrieving the intrinsic parameters to calibrate camera geometrically was crucial, the calibration of depth was as crucial as of the primary concern in using the Kinect v2 depth sensor. Lachat et al. (2015) underlined that there is no unique and universal model for calibrating ToF-type depth sensors. Different researchers found deformation errors in different aspects and addressed the dedicated or combined calibration methods for them.

Hansard, Horaud, Amat, and Evangelidis (2014) noticed that systematic deformation error was partial because of the inhomogeneous modulation process of the emitted IR beams. Lefloch et al. (2013) also reported this systematic periodic ‘wiggling’ error, which caused the ‘oscillating’ depth measurement. The calibration approaches for this phenomenon are less generalizable. Kahlmann, Remondino, and Ingensand (2006) used the look-up tables to store and interpolate the deviations. Lindner, Schiller, Kolb, and Koch (2010) used the method of B-spline curve approximation to model the deviation while Schiller, Beder, and Koch (2008) applied polynomials for fitting the deviation curve. Fuchs and Hirzinger (2008) suggested an error model that compensated distance, amplitude, and latency errors.

The inconstant attenuation of the reflected IR beams from the objects creates the distance measurement shift error. Schiller et al. (2008) investigated the specific calibration steps for the photonic mixer device (PMD)-type ToF camera.

The signal propagation time delay was observed on the sensor array. Lindner and Kolb (2006) considered a per-pixel distance calibration. Kahlmann et al. (2006) suggested ‘pixel-wise fix’ by using filled white circles on dark background.

Other stochastic errors, such as noise were also reported. Kim et al. (2012) proposed the parametric model-based noise reduction algorithm for ToF depth sensors, while Lenzen et al. (2013) utilized some denoising and filtering methods to tackle it.

Similar to the checkerboard in the geometric calibration process, a non-planar 3D calibration instrument that has high-quality geometric precision can be introduced. However, Jung, Lee, Jeong, and Kweon (2015) pointed out the difficulty of manufacturing the 2D-equivalent ‘3D checkerboard' tool in the calibration process. Besides, Lefloch et al. (2013) remarked the difficulty was due to the different imaging modalities between the depth and color. Thus, Jung et al. (2015) had worked out a compromise procedure using a 2.5D pattern board as a calibration instrument. They also proposed the ray correction and range bias correction for the refinement of 3D measurements.

2.8.6.4 Joint Calibration Approaches for RGB-D Cameras

Since the first release of the Kinect and its software development kit (SDK) in 2010, low cost consumer-grade depth sensors have been extensively studied for the purposes of professional usage to exploit its full potentials (Chow and Lichti, 2013; Haggag et al., 2013; Herrera, Kannala, and Heikkila, 2012; Shibo and Qing, 2012; Wang, Shen, Yang, 2014; Wang, Zhang, Bao, 2014). These consumer-grade depth sensors usually combined the color camera and the depth sensor to construct the RGB-D camera. Calibration of the RGB-D camera concerned not only the geometric calibration of two individual cameras but also the depth calibration which was the main purpose of using the depth sensor and other efforts such as matching the color frames with depth frames. Among all these researches, Darwish et al. (2017) reviewed and categorized different methods for calibrating depth sensor cameras as follows:

The first category considered the three sensors within a typical consumer-grade depth sensor including an RGB camera, an infrared radiation (IR) projector, and an IR camera in it, following the pinhole camera model. This concept was then applied in the work of Chow and Lichti (2013), which used the disparity data with mainstream bundle adjustment to calibrate the three sensors. Chow and Lichti (2013) applied the conventional distortion models (Fryer, 1989; Zhang, 2000) for each sensor respectively to compensate for their individual distortion effects. Darwish et al. (2017) commented on the limitation of this type of method in dependency and parameter issues.

The second method was exemplified by the research of Herrera et al. (2012). A comprehensive distortion model was used based on the error behavior of both RGB camera and IR camera. This method had problems indicated by Darwish et al. (2017) in that it limited to the first generation of Kinect, and other flexibility and accuracy problems.

The third category of the calibration method was proposed by Zhang and Zhang (2014). A maximum likelihood estimation was used to refine the in-factory calibration process. The main limitation was that the distortion parameters from the manufacturer for both IR cameras and IR projectors were not dealt with (Darwish et al., 2017).

The fourth category mainly concerned about the depth calibration of the RGB-D sensor. This method was based on the observation equation of depth measurements (Pagliari and Pinto, 2015; Lachat, Macher, Landes, & Grussenmeyer 2015). The method models the error of depth pixel-wise and thus the more appropriate for small objects.

Darwish et al. (2017) also reviewed other calibration algorithms and methods that have been applied and verified including the use of 1D (Liu, Fan, Zhong, and Lei, 2012), 2D (Shibo and Qing, 2012), and 3D (Gui, Ye, Chen, Zhang, and Yang, 2014) calibration objects; Calibrating manufacture parameters (Herrera et al., 2012; Raposo, Barreto, and Nunes, 2013) or photogrammetric bundle adjustments (Chow and Lichti, 2013; Davoodianidaliki and Saadatseresht, 2013). Other works included relative calibration from the IR camera (Macknojia, Chávez-Aragón, Payeur, and Laganière, 2013; Ju, Wang, Zeng, Chen, and Liu, 2013; Kim, Choi, and Koo, 2013). However, these methods had the limitation that the distortion of the IR camera was not completely equal to the distortion of the depth sensor as a whole.

2.9 Confounding Factors Affecting the Depth Measurements

Research teams had reported the Kinect v2 with some unexpected characteristics that might affect the depth measurement other than optic distortion.

2.9.1 Surface Color and Material of the Physical Model

Lachat et al. (2015) also tested the depth-sensing influenced by object surface texture and noticed that reflective and dark objects responded with much greater depth measurements than expected. This finding suggested that when engaging a model in the system, the material and color should be carefully chosen to avoid bias.

2.9.2 Other Interference from Light or Temperature

2.9.2.1 Multiple Reflection

Gudmundsson, Aanæs, and Larsen, (2007) reported the emitted IR beams from the ToF sensor had the issue of multiple returns between the nearby surfaces and causing inaccurate measurement. Precautions about the tabletop surfaces were examined to avoid this situation.

2.9.2.2 Peripheral Light Sources

While the first generation of the Kinect depth sensor cannot function properly in a sunny outdoor setting, the second one is capable, but with some defects. Two phenomena were observed: the amount of 'flying pixels' increased on the verge and decreased with light intensity (Lachat et al., 2015).

These findings were valuable as the proposed interactive tabletop system utilized the Kinect v2 sensor pointing perpendicular to a luminous screen instead of a conventional non-luminous tabletop. The proposed tabletop was designed to be used in normal room lighting or brighter condition, which was different from other systems that operate in a dark room. Thus, the tabletop should expect other environmental light sources such as ceiling lights, and this could create interferences. To achieve a good result, the surface finishing, color, and material of the input model were carefully considered, and the user interface on the touchscreen was designed based on this condition.

2.9.2.3 Noise on Edge of the Image

Shown by an experiment of Lachat et al. (2015), the boundary effect of measurements deviating from the actual distance which has a similar pattern of radial distortion was presented during the test. According to their study, the depth deviations were normally distributed with a 4mm standard deviation.

Corti, Giancola, Mainetti, and Sala (2016) confirmed this phenomenon with a visualization showing the increasing standard deviation of the depth values in the corner along the view frustum. They pointed out readings of corners with standard deviation larger than 15 mm, were therefore not reliable. According to their result, it appeared that the center pixels were more reliable than those on the rim, which suggested the ideal placement of the model. This conclusion gave a hint on tabletop interface design. The central area could be used for the most accurate simulation.

2.9.2.4 Pre-heating Time

Mittet, Grussenmeyer, Landes, Yang, and Bernard (2013) discovered the unreliable sensing readings for some RGB-D sensors as they needed some pre-heating time until reaching a constant variance for the depth measurements. Lachat, Macher, Mittet, Landes, and Grussenmeyer (2015) experimented with checking this phenomenon on the Kinect v2 sensor. Their result showed that the measurements varied up to 6mm for the first 30 minutes. The study of Wasenmüller and Stricker (2016) showed a strong correlation between the Kinect v2 camera temperature and the depth measurement and recommended running the camera 25 minutes before capturing.

The reports above suggested that other than camera optical intrinsic distortion, there were still many external factors that could affect the depth-sensing result. Some of the error was neither systematic error nor stochastic error. They were uncontrollable and unpredictable, and thus unavoidable. While designing the input and output configuration, these factors were taken into account such as restricting material, color, and surface types of the model, setting up moderate lighting environment, and locating the physical model limited in a more centered, 'safe' area on the tabletop, which yields to a higher installation height of the Kinect camera for getting a balanced result.

2.10 Using LEGO as Tangible Input

The architectural and urban design fields have a tradition of using a miscellaneous mixed medium to explore design. Ranging from foam board models cutting with hot wires, Canson sheets glued together, to clay for fast form-finding, much more materials were used solely or combined to reflect design ideas. Typically, different materials were used to differentiate function areas or structures in the design. More often than not, single material was used on purpose to make the viewer focus on the form design itself and achieved a pure and simplistic aesthetic. Among those previous tangible interactive system designs, the researcher used different types of material for their specific reasons. For example, Ben-Joseph et al. (2001) used balsa strips and transparent acrylic plates to build a framework of the volume mass, so that their digitally projective contents can be expressed on the tabletop without the occlusion of the volume themselves. Sareika & Schmalstieg (2010) used cardboards to build the mass and glued them with a printed top image to facilitate a low-cost MR environment. Petrasova et al. (2014) sculpted and cast with polymeric sand for rapid terrain mock-up. These materials served their purposes well in their study. However, when it comes to the general public, it is unlikely for them to use these modeling tools easily. In the search for a much more common modeling tool to successfully convey the idea to the designers, the LEGO was used in this study.

2.10.1 The Basics of LEGO

LEGO is a line of toys with different shapes of plastic bricks that can be interlocked and assembled in various ways. The name 'LEGO' came from the language of the Danish manufacturer, 'leg godt', meaning 'play well'. The current brick form of LEGO bricks was launched in 1958 (The LEGO Group, 2017). LEGO bricks were highly characterized as pixelated and modular and therefore, a suitable input tool of the tangible medium. In the basic set of LEGO bricks, a typical brick is a hull of cubic shape with studs extruded on one side and hollow spaces for the studs to insert on the other side. A standard four-stud block is measured 15.8 mm in length and width, and 9.6 mm in height, as shown in figure 2.4 left. The cylindric studs on the block, measured 4 mm in diameter and 2 mm in height, would be ignored by the Kinect v2 depth-sensing precision. Thus, the LEGO bricks can be imported into the system as flat cubic bricks.

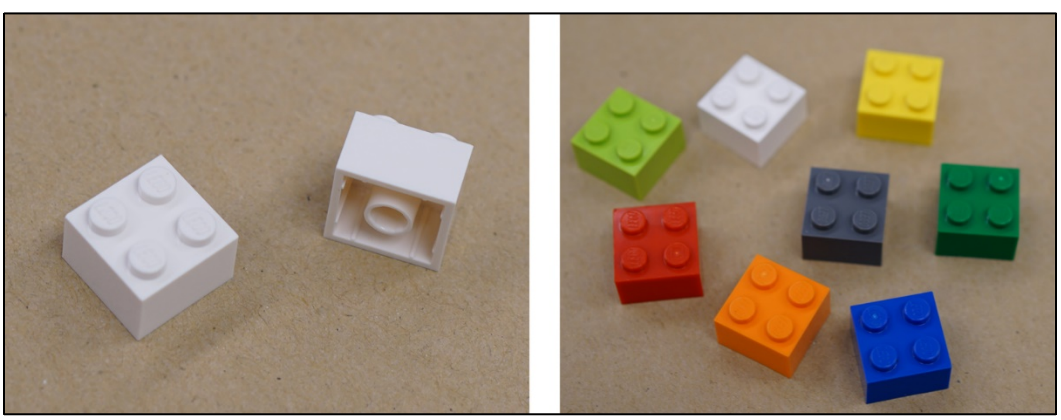


Figure 2.4 Left: The top and the bottom of the white standard 'four-stud' LEGO brick. Right: LEGO bricks are available in many colors, which make it easy for tagging.

LEGO was used as modifiable input in the proposed system, for its modular dimension was closely matched the scale in a typical urban design mass-finding purpose. Besides, there were wide varieties and colors available for the LEGO bricks, which made it easy for differentiating features and labeling highlights in the system.

2.10.2 The Merits of Using LEGO

LEGO nowadays was sold 75 billion bricks every year and was available in over 140 countries (BBC, 2018). There was enough exposure to the public over the decades. Many people have experience playing LEGO or LEGO-like toys since their childhood. The LEGO was also famous for its atomic and versatile metaphor in creating a miniature of the world and thus, welcomed by educational and psychological researchers from worldwide. The concept of LEGO prospered for half the century and expanded to the digital age, such as the video game Minecraft. With its popularity and low threshold to use, the LEGO exhibited itself as a modeling tool with high affordance and clearly as a less time-consuming compared to the professional ones. Although the prevalence of digital touch screens, a recent report (Cooper, 2018) about a nationwide study, conducted by Dr. Dimitri Christakis from Seattle Children's Hospital, showed preliminary evidence that experience with virtual blocks could not replace the knowledge developed by physical tangibility. Because of the reason above, LEGO should be considered the best medium to capture sporadic thoughts from the general public during the charrette activity.

2.11 Summary

This chapter reviewed the existing literature in terms of the concept of smart city and the supporting technologies. The subsequent societal impacts of this paradigm shift were discussed. The cognitive principle and the benefit of embodied interaction, and the application, evolution, and implementation of the tangible interactive systems built upon the theory were also reviewed. The relevant literature on the current system implementations demonstrated limitations in many aspects, which kept it from real-world usage. The list of the identified seven issues of the current interactive system design answered the first research question. To improve this situation, the depth-sensing and calibration were reviewed in detail. Reasons for using LEGO as tangible input in the system for laypeople to perceive, to understand, and to operate, were elaborated according to some literature. In the next chapter, the method of the design process, the implementation of the proposed system and related application would be addressed.

CHAPTER 3. METHODOLOGY

The study was intended to design, develop, and demonstrate the prototype of an interactive system that allowed easy communication, input, and modification of the design in urban design charrettes. The proposed system was expected to decrease the perceptive differences among everyone about an urban development project, which facilitated expressions from the general public to the professionals. This chapter described the methods that were used in the study. The literature review, rationale for the method to the research problem were also presented.

3.1 Approach to the Research

Although there are many design methods about the design principles, practices and procedures in the wild, a systematic process of design was typically dividing the design activity into several phases, regardless of discipline, starting from finding the problem, continuing with clarifying tasks and finalizing with a proposal or deliverable. The UK design council developed a four-phase process (Design Council, 2018) for the creative design: discover, define, develop, and deliver. This study adopted this mapping of the design process and applied several qualitative research methods during each phase. The following sections discussed in detail on the key processes, methods used, and their rationales in this study.

3.2 Methods during Design Phases

Literature review in chapter 2 laid a foundation for a discussion about the research topic and searched for insight into the problem. As a secondary source, the literature review provided an effective and efficient way to understand the latest findings, progress, and trends in relevant fields. This process discovered the potential solution that might not exist in the extant literature and reduced the risk of repeating the same research. The review also validated the need and significance of this research.

3.2.1 Discover Phase

During the 'discover' phase, the context of the problem was set up, and the current study of problem-related areas was explored both in breadth and depth. In this way, the position of this study could be situated within the relevant literature, and possible gaps and the source of gaps could be discovered.

In this study, the fact that increasing urban population i.e., urbanization inferred more and more urban development would be happening in the next decades. With the ICT advances, the opportunities and challenges of the smart city would have a great impact on our daily lives. The technological and societal impact of these disruptive change were reviewed. In the meantime, the author of this study noticed the immense chasm between the ubiquitous digitalization and the heavy traditions of the physical models' usage in the architectural and urban design field. In the urban design charrette environment, the lack of modifiable physical tangibles prevented the general public from expressing their own opinion in a more concrete form. This problem urged a rethinking of the cognitive merits from tangible models. Literature showed evidence of benefits from embodiment. Judging by the author's personal vocational experience in the architectural and urban design field, with research methods such as direct observation, participant observation, and anecdotal feedback from the clients and colleagues, the crux of the problem was identified. A modifiable tangible interface was necessary for the charrette setting.

3.2.2 Define Phase

During the 'define' phase, the focus areas of this research were determined. Since 'tangibility' was identified as the key element solving the miscommunication problem during the 'discover' phase, this work act on introducing and centering tangible into the tabletop system.

A quick case study about existing tangible interactive tabletop systems was conducted in the chronological order at the end of chapter 2. Researches about different types of existing interactive tabletops were summarized, and a timeline of tangible tabletops evolution was presented as a conclusion. As a qualitative research method, more and more features and benefits in utilizing tangible objects were found and summarized. It became clearer that the physical objects would play a central role in the future system design. By analyzing previous designs, problems unsolved by previous researchers were reconsidered and redesigned in the new context. The principles of developing the system were based on the UD Co-Spaces solution (Mahyar et al., 2016), which is the seven urban design charrette principles: 'engagement, collaboration, interactive visualization, accessibility, iteration, understanding consequences, and transparency'. From the vantage of this research, 'tangible interoperability' was equally crucial together with the other seven principles. The new principles framed the design challenge of the proposed system. Literature about proxemics and ideal form of system set up were also explored. The proposed interactive system should be able to accept the constructible miniature model as input, which gave everyone a sense of control and other nonverbal communication advantages on the models about the urban design context.

The centerpiece for the system to understand tangible objects input, the Kinect v2 camera, and its SDK, was easy to access and implement. This study selected the Kinect v2 camera and used its depth-sensing camera in the system. To ensure accuracy of volume awareness, the principle of depth-sensing technology, detailed camera calibration methods, and factors about using the Kinect v2 camera that could affect measurements were also reviewed. These researches revealed the disadvantages of using the Kinect v2 camera as a measuring tool, which raised attention and awareness of constraints during the 'develop' phase.

The reason and rationale of choosing LEGO as a tangible input medium was explained in chapter 2. It was a choice of high compatibility with the depth sensor, as the sensor can monitor the changes of LEGO in real-time. Therefore, it was necessary to have a tangible input which is easy to modify. With the help of the modifiable tangible models, users from different professions and backgrounds were expected to have better understandings and expressions of the design intention, which in turn started co-working on the design project.

3.2.3 Develop Phase

During the 'develop' phase, problems of previous systems were summarized, and potential solutions were explored, prototyped, and refined in iterations to fulfill the need of the general public users in an urban design charrette setting.

The development of the system was documented as essential elements along the system pipeline. In this way, the procedures, equipment, and corresponding rationale for a specific problem were presented. The element-centered solution established a logical design path and process to describe empirical good design practices. Therefore, the product of this study would have much more generalizability over specific guidelines because this knowledge can be reused later, even in interdisciplinary studies. Each of the element entry worked as a single solution to a design problem within a specific context. The elements can be integrated into each stage of the system pipeline for a charrette-like design scene. Ultimately, the elements altogether, in a bigger picture, served as their respective roles in the system, with power more than individual added together. The elements list consisted of an unexhausted manifesto according to actual needs. The element entry itself would be typically documented in the following format:

1. Name: Concise, descriptive name of the element for easy communication.
2. Description: Additional explanation to help understand what the element does.
3. Problem Statement: Addressed in reader-centric, description of the problem that the element was to solve.
4. Context: The condition when the solution applies.
5. Solution: Explanation of how to solve the problem.
6. Rationale: Further explanation about the reasons why the solution works.
7. Examples: Successful case demonstrated by a short description and image(s).
8. Comments: Notes or Discussions about the use of the element.

This form of documenting elements excelled at capturing and explaining common knowledge in plain language and reducing the time and costs in many use cases and scenarios. In chapter 4, the element list followed the format above to introduce the implementation of the system design.

3.2.4 Deliver Phase

During the ‘deliver’ phase, the prototype system was finalized and tested to ensure it addressed the problem it was built to solve. Information about user satisfaction and suggestions were gathered and analyzed to inform future directions and improvements.

Because of the open nature of the research questions, the disparity of the urban projects, and the varying participant’s individuals, qualitative methods were considered a proper approach to conduct the assessment of the system. In this study, heuristic evaluation (Nielsen & Molich, 1990), a usability inspection method developed for human-computer interaction (HCI) was used to identify usability problems of this prototype of tangible system interface design. The advantages of using heuristic evaluation were it requiring significantly fewer subjects and less time in the experiment, yet effectively uncovered major issues of the system usability. Previous researches (Lewis, 2006; Turner, Lewis, & Nielsen, 2006; Virzi, 1992) showed that more than 80% of the severe usability problems could be revealed by a participant's sample size of five. The heuristic evaluation was, therefore, an economical and appropriate method at the early stages of product development, such as the prototype system in this study. The 'heuristics' were a set of well-recognized principles or rules to be assessed in the heuristic evaluation. The detailed heuristics and descriptions related to each heuristic could vary based on the purposes and the users. Defining a set of heuristics that was aiming at the targeting prototype was essential to the evaluation. Chapter 5 discussed the process of heuristic evaluation in detail.

3.3 Threats to Validity

This study stemmed from an interdisciplinary context between design and technology. The chosen research methods came with unavoidable trade-offs between the valuable open opinions and large-scale rigor responses. There is a risk proven by experience that improper validity criteria would lead to either incompleteness or pseudoscience (Whittemore, Chase, & Mandle, 2001). In this research, challenges constantly came from neither overemphasis too soon on the process for allowing creative alternatives, nor be meticulous on the solution for better generalizability.

As a prototype of a developing system over a manufacturable final product, the deliverable of the system design was far from mature. Although the results of the research reflected the experience of the evaluators and suggested high credibility, external validity such as participants in a real-world situation requires further discussion.

During the research, the location was highly limited due to the bulkiness of the system. This inconvenience prevented the system from being deployed in more publicly accessible and populated places (such as in the center of a residential community). The participants might not have real vested interest involved in the selected urban project site in this study. This quasi-urban design charrette condition weakens the validity and credibility of the research. However, the focus of this study was a prove of concept in a specific scenario, and to capture best practices and approaches in designing and developing this kind of system. The used methods were justifiable for yielding meaningful insights into the research problem.

3.4 Summary

This chapter described the methodology used in this research. Approaches to the overall research, qualitative methods during the four design phases were introduced. The limitation that can jeopardize validity were also discussed.

CHAPTER 4. SYSTEM DESIGN

This chapter describes the system development process in answering the second research question. To begin with, the problems of previous systems were summarized and elaborated. The author's previous experience in urban design charrettes, together with the current system problems, was organized into the design requirements. To implement the prototype system, individual components, and essential procedures in the system were defined through elements description along the system pipeline. The purpose of documenting these elements usages was to 1) elaborate the function of each part of the system, and 2) provide an optimized solution to a recurring problem under certain condition, so that it could be used immediately in a later time in the same situation without reinventing the wheel. Elements were interrelated by the system pipeline, layers, and interfaces in each stage towards immersive analytics. The construction of the mapping relationships provided ingredients useful to a similar application that was more knowledgeable and meaningful than single discrete solutions.

4.1 Problems Unsolved in the Previous Systems

As reviewed in section 2.7, the current solutions barely support direct modification to the shape of the urban mass models on the tabletop. Although some of these systems were able to detect the pre-set shape of the model, it was time-consuming to construct a new model to enable the charrette design iterations. The following list provided the answer to the first research question. In sum, these solutions suffered from defects in:

- Inflexible (unmovable and/or unmodifiable) Tangibles. The tangible objects were fixed on the table base. Once the model was placed on the tabletop, there was little chance to make a change to the model. In this case, the model was only presentational and finalized.
- Lacking Volume Awareness. The missing functionality of the volume detecting was highly associated with the inflexible tangibles. The shape of the tangible objects was irrelevant to the design. If the tangibles do not change in shape, it was meaningless to monitor the tangibles. Current systems could not detect shape changes.

- Pre-set Design Alternatives. Only a limited alternative of design could be selected. This problem was largely due to the difficulties in preparing models for those non-modifiable tangibles. The model may be in a high degree of completion and fine quality. However, not supporting arbitrary designs and the high cost in the design process hindered the exploration of good designs.
- Coarse Resolution. The tangible objects mostly served as physical symbols or individual information panels on the tabletop. This was due to technology limitations in earlier ages. The systems were not precise enough to locate the position or orientation of the physical models.
- Projection Occlusion. There was limitation using projectors as the outer part of the objects might blocking inner parts at some angle. Occlusion created shadows on the tabletop or the models themselves and created unwanted patterns that might interfere with the analytics.
- Operable Only in the Dark. The heavy use of projectors made it barely legible in the normal room lighting condition. Although the projectors provided a high contrast image in the system, receive information other than the tabletop system such as paper-based documents at the same time was impossible.
- Exclusive to a Single User. Equipment dedicated to single users such as VR/AR helmet impeded equal communication.

These problems put obstacles in the way of collaborative design activities. Without the participation of the general public, the interactive system reduced to a merely presentational tool. More importantly, it was difficult to convey the design idea from layperson to the professionals. These solutions lacked the flexibility of modifying the tangible objects which reduced them to demonstration tools rather than design exploration tools. These systems did address one or a few perspectives of the urban problem. However, it required much more information integration for a successful co-design process. The proposed system was explicitly designed to address these problems by introducing the depth sensor.

4.2 Design Requirements

The target users of this prototype system were stakeholders in the urban design charrettes. Stakeholders could come from various backgrounds and with expertise very different from urban design. Based on the previous observation and interviews by the author in the past charrettes, the typical demands from the stakeholders and the associated elements include:

- Many people wanted to change the display model, but the urban design models were challenging to make. Literature from section 2.4 pointed out the importance and benefits of users' direct perception and operation with the physical model to express their opinion and ideas. In this case, the element of 'Modifiable Tangible' was introduced.
- Participants often used multiple media at the same time. Although the tangible tabletop played an essential role in the urban design charrettes, many supporting paper-based documents were still handy in the discussion. Cross-reference between textual, legacy regulation drawing, and the physical models was still a strong need in this situation. A tabletop capable of both digital and physical contents was preferred. Participants sometimes unconsciously and casually left the documents on the tabletop and started to interact with the models. Thus, the concept of 'Safe Space' was brought in to define an area of the depth-sensing.
- People had little sense of the full image of the site. As indicated in section 2.4, people without professional training have limited awareness of the site situation. Previous charrettes only showed photos from convenient or pre-selected angles of the site. Sometimes the problems were under-informed. To observe the 'transparency' principle in information exchange that everyone should be well informed, an integrated 'Street Panorama' would help to understand the current site condition.
- Stakeholders needed to know the consequences of intervention in time. Previous charrettes either had no interaction at all or provided a time-consuming simulation that often took hours to complete. This lagged feedback left the stakeholders to speculate the impact with unexpected problems. The 'Simulation Module' in the proposed system utilizing depth-sensing data, was developed to process the depth data and to show the real-time consequences for a fast proof of design idea.
- Users needed to know the overall situation of what was going on in the model 'sandbox' in a more understandable way. Due to the limit capacity of an interactive tabletop and the

population in a typical charrette, a clear bulletin-like display must in place for the participants not operating the tabletop. A secondary information screen wall was implemented for this purpose.

- Design ideas and discussions were happening at a fast pace in the charrettes. The potentially viable solution could be forgotten and lost in the discussion if not recorded in time. Valuable design alternatives were transient during the modification of the models and they were sometimes difficult to describe verbally. The functionality of recording the history of changing models was an actual need for modifiable interactive tangible systems.

Elements directly addressed for stakeholders' needs also called for other indirect, infrastructure elements that supported or facilitated them. The following sections documented these essential elements for the prototype system in the four layers during the three stages of the system pipeline.

4.3 System Pipeline

The essential elements of the proposed system were identified during the initial incremental and iterations of system development. The pipeline which orchestrating the system, comprised of three major stages: 3D reconstruction, processing and analysis, and visualization. At each stage, four layers: hardware configuration, software environment, screen interface design, and tangible interaction design, worked in parallel from infrastructure to interaction, as depicted in figure 4.1.

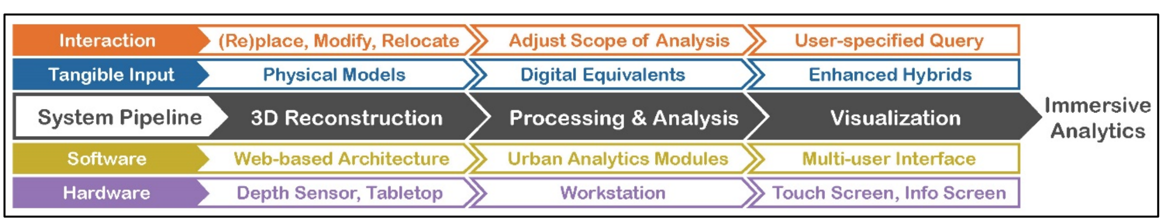


Figure 4.1 The three stages of system pipeline towards immersive analytics: 3D reconstruction, processing and analysis, and visualization. Along with the pipeline, the hardware and software served as the infrastructure layer, while the tangible input and associated interaction served as a tangible interface to the users.

In the 3D reconstruction stage, the user interacted with the tangible objects, while the depth sensor captured the change in shape and volume, simultaneously porting the data to the system and reconstructing the depth map to a 3D shape then porting to a web-based application. In the processing & analysis stage, the user interacted with the tabletop system to adjust the scope of analysis, and the reconstructed digital model was then entering the urban analytics software packages for further analysis. In the final stage of visualization, the user-specified contents of analytic results as needed to express urban design ideas. More users may be entered in this stage. With visualization displayed around the physical model, the physical model now became the digitally enhanced hybrid in the system. The modifiable tangible input played an important role throughout this pipeline. Since the system captured the change of physical model in real-time, the corresponding interactive hybrid visualization created an immersive analytics environment.

4.4 System Design Elements

The remainder of this chapter documented vital design elements for the proposed system in detail. The system design elements were categorized and established in the four layers defined above in the pipeline alongside with the modifiable tangible input.

4.4.1 Modifiable Tangible Inputs

- Name: Modifiable Tangible
- Description: Physical modifiable objects being placed on the tabletop.
- Problem Statement: The urban design models were challenging to make and change by the general public.
- Context: Equal and fast input from shareholders during urban design charrette.
- Solution: Use easy to assemble, easy to disassemble, modular tools such as LEGO.
- Rationale: Lowering the threshold to modify the model promotes proactive discussions in urban design issues.
- Examples: As shown in figure 4.2, with LEGO bricks, design alternatives can be made within a minute by the participant.
- Comments: As the tangible inputs for the proposed system, the change of location, size, height, shape, and color of the physical objects could be immediately captured and recognized by the RGB-D camera. With depth-sensing, regardless of the material,

ad hoc working models (such as paper, wood, or foam) and other prototyping instruments such as LEGO bricks, 3D printing models, or even Play-Doh could be accepted for flexible scene construction and modification. The modifiable tangible input opened up many possibilities of alternative designs that could be easily modified, perceived, and understood by everyone without induced much extra cost.

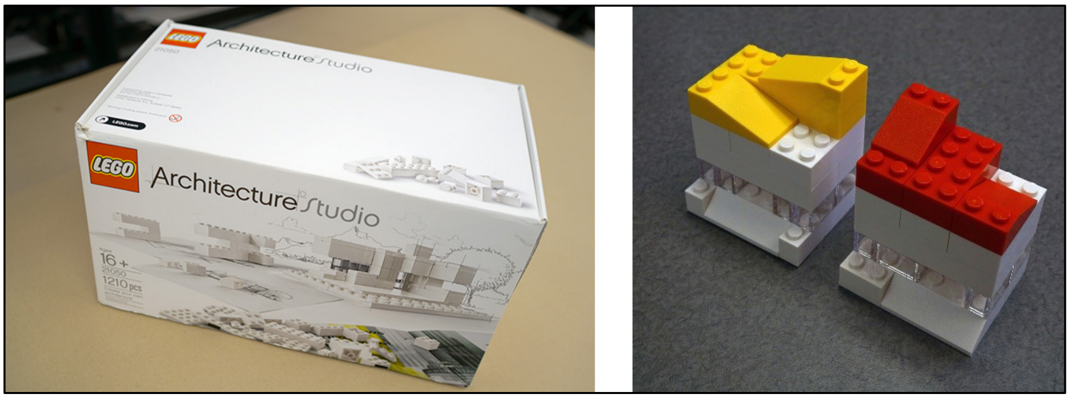


Figure 4.2 Left: A set of LEGOs themed 'Architecture Studio' was developed in 2013. Right: Two alternatives rooftop designs with different colored LEGO.

4.4.2 Tangible Interaction Design

The tangible interaction design concentrated on how to make the physical model enriched and informative. Unlike previous systems, the physical models used in the proposed system were fully movable and modifiable during the entire process. While operating the physical model, the users tended to focus on the object at hand narrowly. The design of visual cues should 'follow' the physical objects, providing in-situ and immediate feedback and instructions.

4.4.2.1 <u>Defining Safe Space for Tangible Input</u>

- Name: Safe Space
- Description: Tangible functional areas on the touchscreen.
- Problem Statement: Physical objects casually left on the tabletop would interfere with the depth-sensing result. Camera distortion deteriorated at the rim. Always-display panels occupied too much the screen space.

- Context: Tolerance of novice users. Need to reduce inaccurate results. Leaving spaces for touchscreen interaction.
- Solution: Define a small area at the center of tabletop specific to tangible interaction.
- Rationale: Extra room on the rim of the screen was needed for the placement of non-engaging objects, casual hand rest, and interface panels.
- Examples: In the prototype system, the volumetric space above the touch table surface was designed to accept tangible inputs and performed tangible interaction. A much smaller volume was defined as a safe space, as depicted in figure 4.3.
- Comments: Due to the hardware selection (The Kinect v2 camera) and the scale of LEGO, a volumetric space of a 500mm by 500mm by 900mm was defined to be the tangible interactive zone for the best result. The central area of the screen was utilized for depth-sensing to minimize the optical distortion of the camera lens. In the meantime, some space on the rim of the touch screen was left for control dashboard panels and legends. The area of the tabletop surface other than the safe space was left for the casual placement of paper-based documents and hand rest.

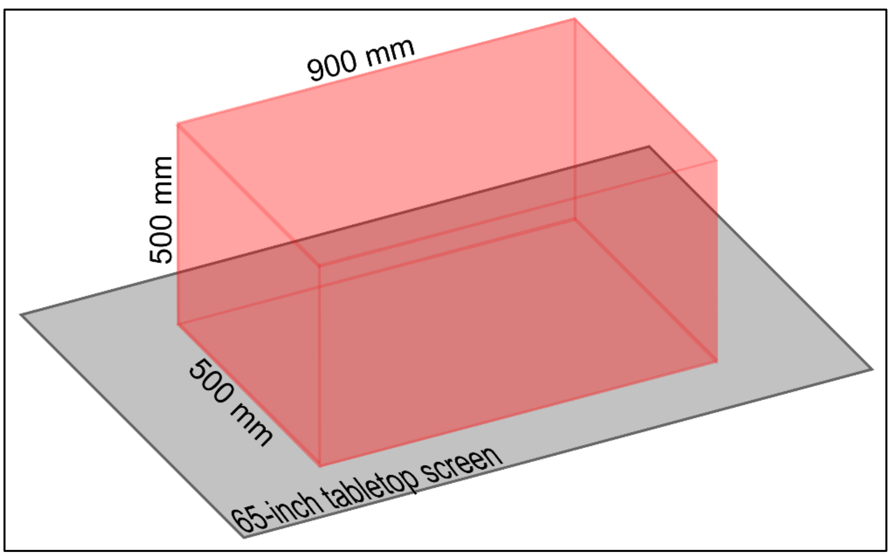


Figure 4.3 A safe space that is defining the effective interaction area was depicted as a red bounding box in this diagram.

4.4.2.2 Providing Area Sorter for Scale Awareness

- Name: Area Sorter
- Description: Tool for comparing the tangible models with the on-screen legend.
- Problem Statement: The size and scale of tangible objects were difficult to perceive.
- Context: The users need a reference of the current scale of tangible models to the map.
- Solution: Implement an area legend instead of length legend for easy comparison.
- Rationale: According to Cleveland's graphical features hierarchy (Cleveland & McGill, 1985), the area and the volume were among the least rankings in information transfer.
- Examples: An interactive area sorter legend was provided in many combinations of LEGO bricks to aid the user to compare the area of the newly-created blocks directly. The displayed area on the legend can change according to the map zooms, as shown in figure 4.4.
- Comments: A legend with a great resemblance to the tangible model at hand can help alleviate the situation. The displayed interactive area annotation was not rounding to 10s and 100s for the Google Maps API only provided the zoom level in the step of an exponent of base 2.

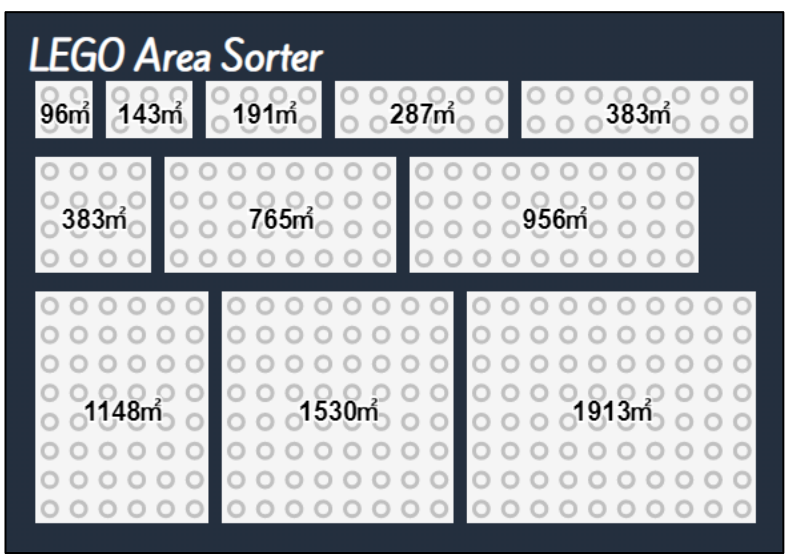


Figure 4.4 The area sorter uses the LEGO stud feature to remind the user with good affordance. The number in the center of piece changes according to the map scale.

4.4.2.3 Placing Capacitive Dial for Easy Street-view Control

- Name: View Controller
- Description: A tangible token object to represent street-view panorama orientation.
- Problem Statement: Orientation representation on the horizontal tabletop touchscreen required mapping to the vertical street-view panorama, which increased short-term memory load.
- Context: The vertical screen is not a touch screen.
- Solution: Use a capacitive dial to embody the 'Pegman' role in Google Maps as a street-view orientation indicator.
- Rationale: The view controller resembled a volumetric arrow-like object, which gave good affordance about the orientation of the street-view. Once the dial was placed on the tabletop, the street view orientation was set to the corresponding direction and the walking distance area was drawn on the map.
- Examples: The view controller was modified from multiple capacitive stylus tips. The stylus tips were attached to a mass made of metal and were pointing to the touchscreen. When the user made contact with a few fingers through the metal dial to the touch screen, the human body electrostatic conductivity created a unique pattern (pre-defined by how stylus tip was arranged) that a system could recognize.
- Comments: The capacitive dial was designed as a location- and orientation-aware, assignable token object. However, the actual usage in the prototype system was less than satisfactory. The tangible nature sometimes confused the user, and it was often misplaced into the map. Further research about improving the sensitivity of contact tips to the touchscreen is required.

4.4.3 Screen Interaction Design

The elements of screen space in the user interface were positioned according to its natural and intuitive daily usages so that a good affordance could be achieved. For example, the map was placed horizontally on the touch table, while the street views and head-up information for overview were placed on the vertical screen. Another example would be the alignment of the map view and the skyline view across different screens so that the users could immediately utilize the analytics without mental mapping efforts.

4.4.3.1 Interface Layout for Simultaneous Multi-users

- Name: Multiuser Layout
- Description: A touchscreen tabletop interface that can engage multiple users.
- Problem Statement: Typical interaction layout allowed only a single user at a time.
- Context: The operation requires a collaborative design.
- Solution: Design multiple and duplicated set of the control panel for each side of the screen.
- Rationale: In case of user need to reach a function button at the opposite end of the tabletop, the occlusion of the physical model on the tabletop becomes a problem. The user must walk around the table to access some functions and information. Frequently used control buttons, status, and legend on the tabletop screen should be duplicated and orientated to the user standing on the corresponding sides of the table.
- Examples: Figure 4.5 demonstrates a layout design for multiple tabletop users.
- Comments: The screen space interface design required consideration for collaborative and participatory urban design factors in the application. This requirement yielded a slightly different design from those for a single user.

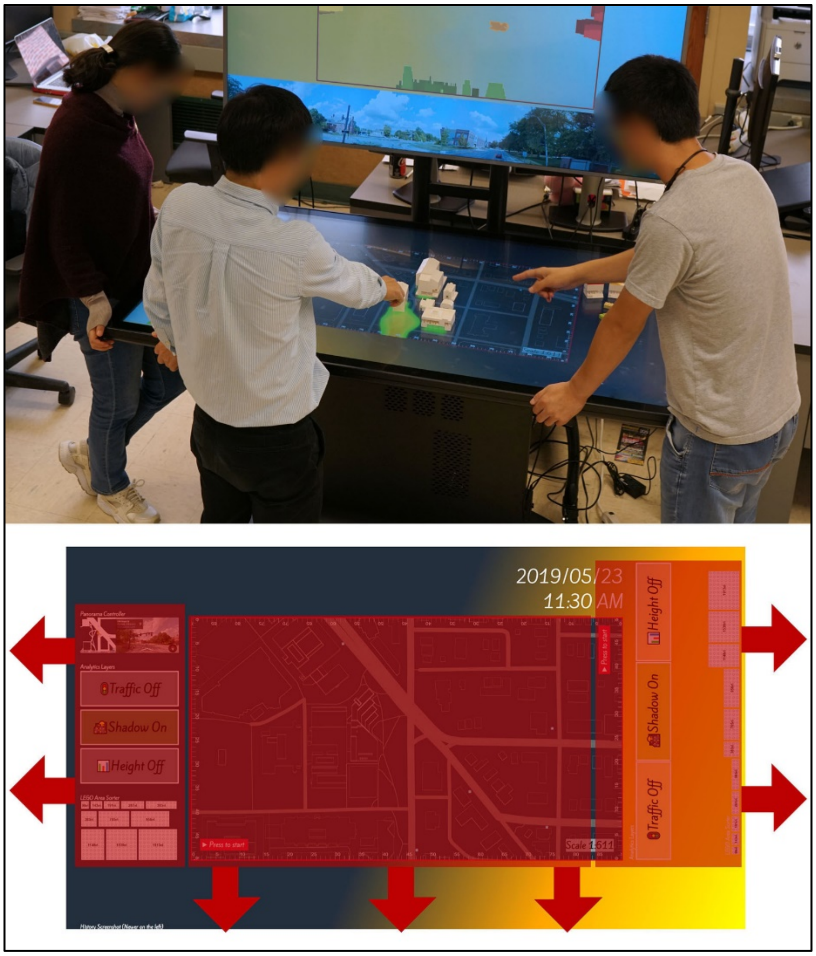


Figure 4.5 Upper: The tabletop interface was designed to be approached in various directions. The maps and panels are serving users from different orientations towards the tabletop, especially for the users from left and right.

4.4.3.2 Peripheral Awareness for Contextual Perspective

- Name: Daylight Background
- Description: The height and position of the current scene of the Sun simulated in the background.
- Problem Statement: On the simulation tabletop, users often lacked the sense of the natural environment.
- Context: The user needs to know the solar condition of a specific time on a specific date.
- Solution: Calculate the azimuth and altitude of the Sun and show it in the background.

- Rationale: When a user selected a location area on the map and specified the date and time, the current azimuth and the altitude of the Sun would be visualized as an orange radial gradient speckle on each of the blue background of the screens (when the Sun is above the horizon). This visual linkage cue reminded the users of the current sky environment and help the users make better judgments about shading conditions.
- Examples: As designed in figure 4.6.
- Comments: To better mimic a sky of clear weather, the default background color should set to blue.

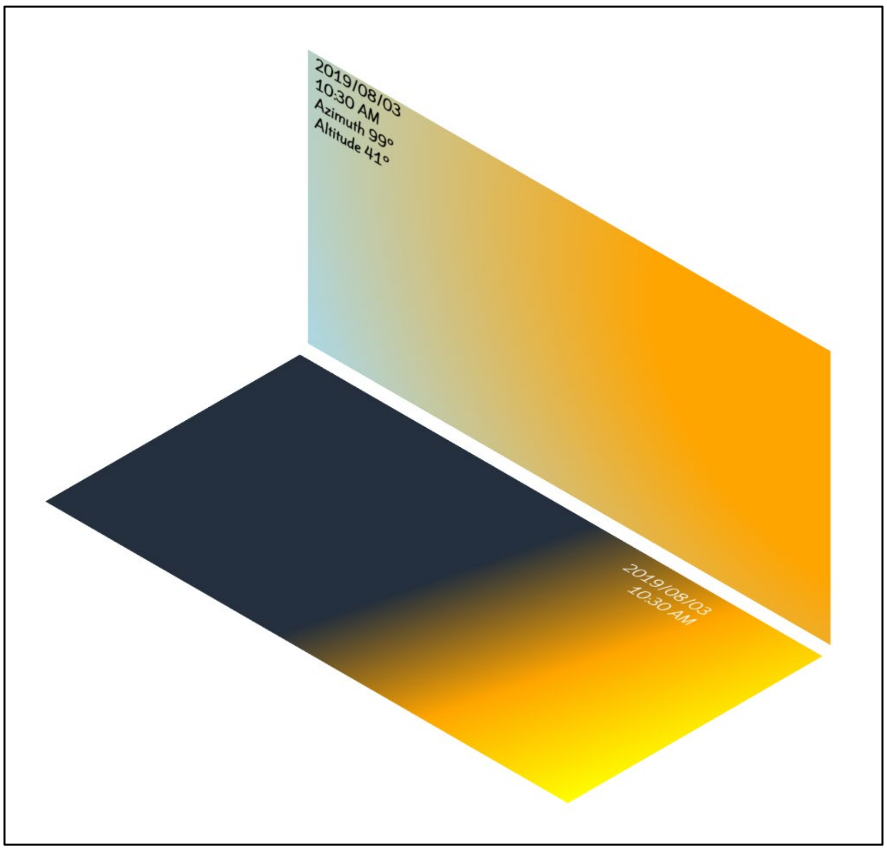


Figure 4.6 A solar simulation of Aug 3, 2019, at the two backgrounds. The centers of the orange aurora on the blue canvas indicate the altitude and azimuth of the position of the Sun.

- Name: Street Panorama
- Description: A direct panorama photo to show peripheral site conditions.
- Problem Statement: Charrettes often provided a limited angle of photos from the target site, which sometimes misleading.

- Context: The street-view is available at the site.
- Solution: A surrounding panorama street view according to the Google Maps 'Pegman' location can be provided interactively on the information screen for awareness of the site peripherals. This is made by stitching the street view images in four principal orientations.
- Rationale: The Google street view is an excellent source to explore site conditions as it updates regularly. Using the provided API, design renderings can be overlaid on top of the street view images.
- Examples: Figure 4.7 demonstrates the construction of a panorama photo from Google street views.
- Comments: A control of the panorama facing direction should also be implemented.

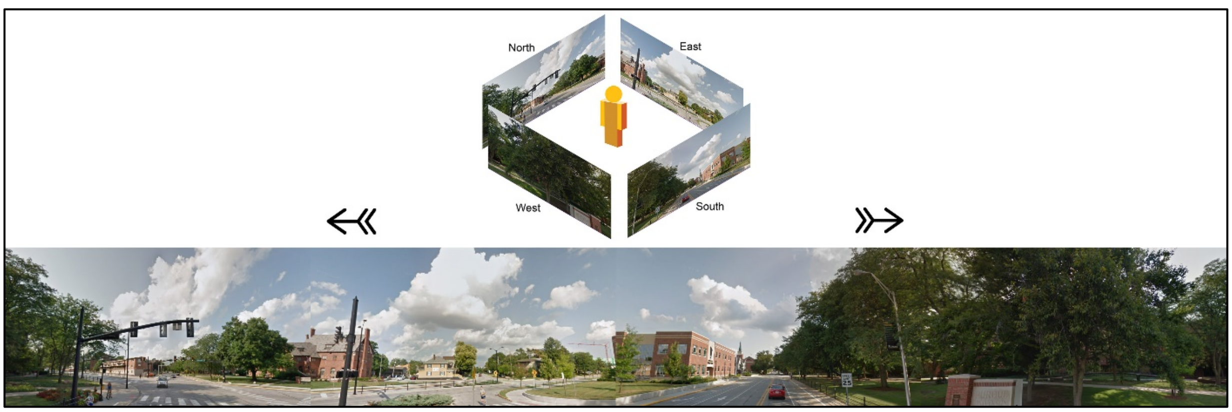


Figure 4.7 Upper: The street views were retrieved in the four interrelated orthogonal directions. Lower: The four street views were stitched together to form a panorama view of the site. Users may rotate the pegman to specify the arbitrary center of the panorama.

4.4.3.3 <u>Real-time Simulator for Impact Assessment</u>

- Name: Simulation Module
- Description: Software application to generate impact simulation.
- Problem Statement: Digital simulated contents were not informative and real-time as physical models change.
- Context: The depth-sensing is applied in the system, and the shape can be analyzed.

- Solution: The depth data streams of location, shape, and height of these physical objects can continuously enter the system. The urban analytic software package can then be activated when the shape of the physical model is digitally constructed.
- Rationale: The simulation could visualize the impact in real-time. For instance, the shade would be cast according to the objects' heights at the current map scale and the current solar position. In the traffic simulation, the user can estimate the street pressure once the physical blocks are placed on the map.
- Examples: The shade simulator and street impact simulators were implemented in this prototype system as in figure 4.8.
- Comments: This function helps the users understand how a certain development project would create an influence on peripheral areas at any specified time. Also, they were able to move around or modify the building blocks to test alternatives in real-time.

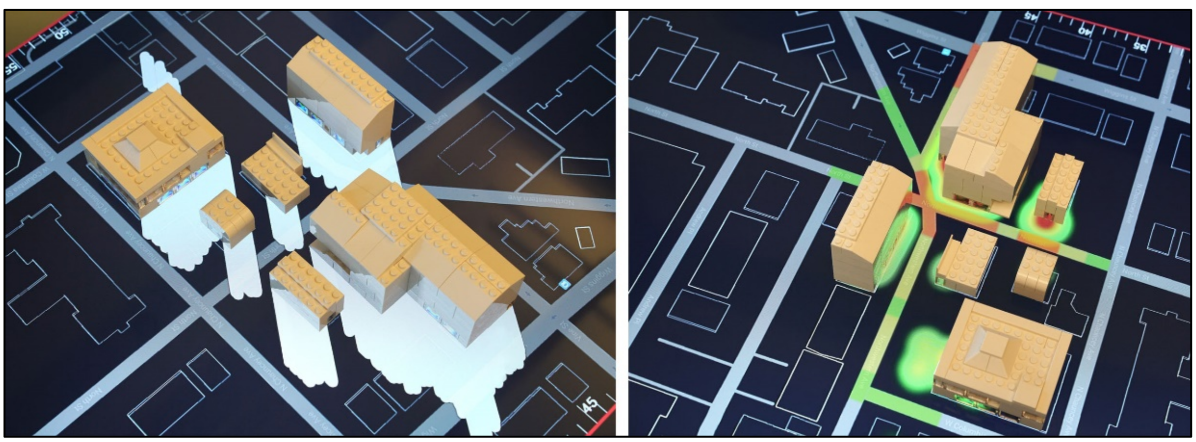


Figure 4.8 Left: A close-up of the shadow simulation according to a specified date and time. Right: A close-up of the street traffic impact simulation based on model shape and height.

4.4.3.4 Interaction History for Solution Comparison

- Name: History Snapshot
- Description: A record of the interaction history of the system.
- Problem Statement: The design ideas would be lost in the design iterations.
- Context: There is a need to compare and discuss the different design alternatives.

- Solution: A history snapshot functionality was added to capture the map interaction activities on the system for future side-by-side alternatives comparison between different users or different time.
- Rationale: This kind of history functions were necessary for the tangible model on the tabletop would be modified and relocated at a fast pace during each design iteration.
- Examples: Images of the current model set up, and contents from the digital analytic map on the tabletops were recorded.
- Comments: An internal activity history of the interaction makes the discussion easier.

4.4.4 Hardware Configuration

The choice of hardware components was based on collaborative users' needs in the urban charrette setting. Selected components should be easy to find, easy to access, easy to deploy, and thus, easy to modify, easy to maintain, and easy to substitute if a particular component was discontinued or became dysfunctional. Highly sophisticated consumer-grade components were used to make the system highly modularized, which provided abundant alternatives.

4.4.4.1 Tabletop Space for Collaborative Interaction

- Name: Collaborative Venue
- Description: An installation, typically the top of the tabletop, for tangible interaction with multiple users.
- Problem Statement: Ambiguity and off-focus spaces were inefficient for collaborative design.
- Context: An organized discussion for multiple users is needed.
- Solution: Use a physical installation that is outstanding enough to attract potential users.
- Rationale: The bulkiness and luminosity of the large tabletop could easily attract users' attention from far away. It was a good starting point to gather the users around the table. The tangible tabletop was not only a surface that holds the ready-to-engage objects but also established a rendezvous for discussion.
- Examples: Commercialized touch screen tabletop used in this study was typically designed for museums. The tabletop touchscreen provided the in-situ information and

interaction around the tangible objects. Users could visualize and interact with street-level information and other general operation, such as changing scene dates and time.

- Comments: The Ideum Platform touch table embedded with an LG 65-inch television in 4K resolution, supported by the main chassis underneath as depicted in figure 4.9. The touch screen equipped a 3M electronics 80-point functionality. The PC system configuration used in this study was as follows: Intel (R) Core (TM) i7-6700K CPU @ 4.2GHz processor, GeForce GTX 1070 graphics card with 8GB video memory, 16384MB RAM system memory, and 512GB SSD.

4.4.4.2 Overhead Sensor for Data Input

- Name: RGB-D Sensor
- Description: A sensor that captures both color frames and depth frames.
- Problem Statement: The change of color and shape of the physical model was not recorded. The system could not analyze information other than location and orientation.
- Context: Analysis of color and shape change of the physical model is needed.
- Solution: The RGB-D sensor was employed to monitor the interactive changes made by users with the physical objects on the tabletop.
- Rationale: The RGB-D sensor was to extract the size, location, and height of building blocks on the tabletop. Since the proposed system design centered on physical models that were continually modifying by the users, the sensor itself should be concealed or insensible to the users so as not to interfere with the interaction.
- Examples: The depth sensor was hanged above the vertical screen, pointing to the center of the tabletop, as shown in figure 4.9. All the activities on the tabletop could be monitored.
- Comments: The off-the-shelf consumer-grade RGB-D camera such as Microsoft Kinect in this study was initially designed as a contact-less interactive component for body or face tracking, gesture or pose recognizing the device on the Microsoft XBOX video gaming console system. Its low cost, high portability, and high speed made it possible to perform the rapid 3D reconstruction.

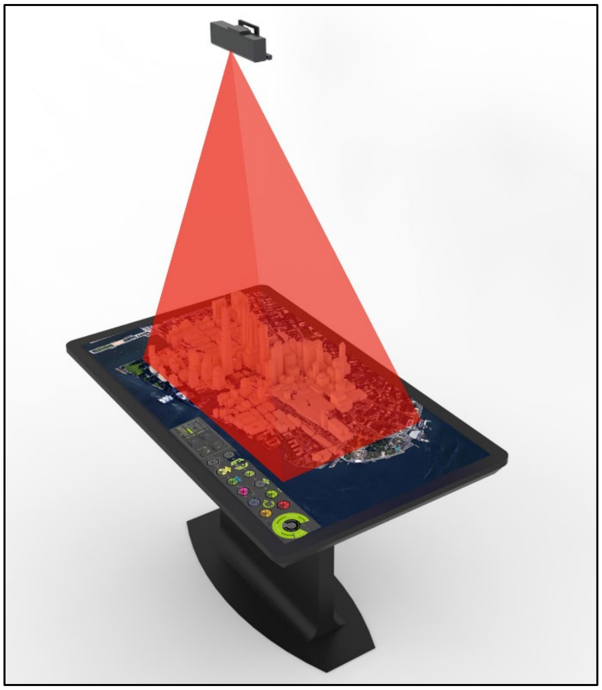


Figure 4.9 A rendering is showing the Kinect v2 camera was installed right above the tabletop, using infrared to generate a depth map.

4.4.4.3 <u>Determining the Installation Height of Kinect v2 Camera</u>

- Name: Sensor Height
- Description: The calculation method and the result of the height of the sensor in order to function well.
- Problem Statement: The exact height of the sensor being hung above was unclear, which could underutilize in terms of precision or cause cut off in shape sensing.
- Context: The used type of RGB-D sensor is Kinect v2. The sensor is hung right above the tabletop.
- Solution: If the height h_{scene} of the highest point in the model scene was known, the Kinect camera should be mounted at least $h_{scene} + 0.5m$.
- Rationale: Refer to the paragraphs after 'Comments' of this element entry.
- Examples: The suggested height h of sensor C was hung above the tabletop, and the geometric relationship was depicted in figure 4.11.
- Comments: In this study, the actual Kinect v2 camera was installed at the height of 3 feet and 10 inches (1180 mm) to reduce radial and tangential aberration from the

camera lens without the additional computational cost of calibration. The maximum height of the physical model was set to 1 foot and 11 inches (590mm) for better precision.

The view frustum is the truncated pyramid-shape space representing the ideal cone of view that can be ‘seen’ by the camera. The view frustum model defines the six-facet confined space that is of primary concern in the camera model. Anywhere outside of this region will not be seen by the camera. Along the direction at where the camera is pointing at, from near to far, two parallel planes are: the near plane and the far plane which define the minimum and maximum distances that a camera can ‘see’ in-between. To fully make use of the Kinect camera, the space above the touchscreen tabletop should be fully covered by this view frustum.

According to the Kinect for Windows SDK 2.0 documents (Microsoft Docs, 2014), The ‘WindowsPreview.Kinect’ namespace has ‘ColorFrameSource’ class and ‘DepthFrameSource’ class, which both report ‘FrameDescription’ members respectively, which containing the Width and Height attributes in pixels and the ‘HorizontalFieldOfView’ and ‘VerticalFieldOfView’ attributes in degrees. The Kinect v2 camera has a color image resolution of 1920 × 1080 pixels and a field-of-view of 84.1 × 53.8 degrees resulting in an average of approximately 22 × 20 pixels per degree. And it has a depth image resolution of 512 × 424 pixels with a field-of-view of 70.6 × 60 degrees resulting in an average of approximately 7 × 7 pixels per degree. The touchscreen table to be used in the proposed system equipped with a 65-inch (diagonal 64.5 inches, i.e., 1638mm) screen in a 16:9 aspect ratio. The actual length and the width of the luminous area of the screen, i.e. the pixel array is measured to be 56.2 inches (1428mm) by 31.6 inches (803 mm). To fully utilize the RGB color camera and the depth sensor specification, both length and width of the far clipping plane that construct the Kinect v2 camera view frustums, for both color camera and the depth sensor, should both cover the pixel area.

With the knowledge of trigonometry, let C be the center of the camera at the desired height. The pose of the camera is pointing perpendicular towards the touchscreen table surface. The point Q on the tabletop is the foot of the perpendicular line CQ to the tabletop. Thus, $\|CQ\|$ is the height h of the pyramid of vision as shown in figure 4.10, which is also the desired height about to solve. L is the long side midpoint of the base rectangle of the view pyramid, and W is the short side midpoint. It is evident that QL is parallel to the short sides, and $\|QL\| = \frac{1}{2}w$.

And similarly, QW is parallel to the long sides with $\|QW\| = \frac{1}{2}l$. In the right triangle CQW, the following relationship holds,

$$\tan\frac{\alpha}{2} = \frac{l}{2h_h}$$

The minimum height h_h for the horizontal field of view that covers the tabletop is solved in that

$$h_h = \frac{l}{2\tan\frac{\alpha}{2}}$$

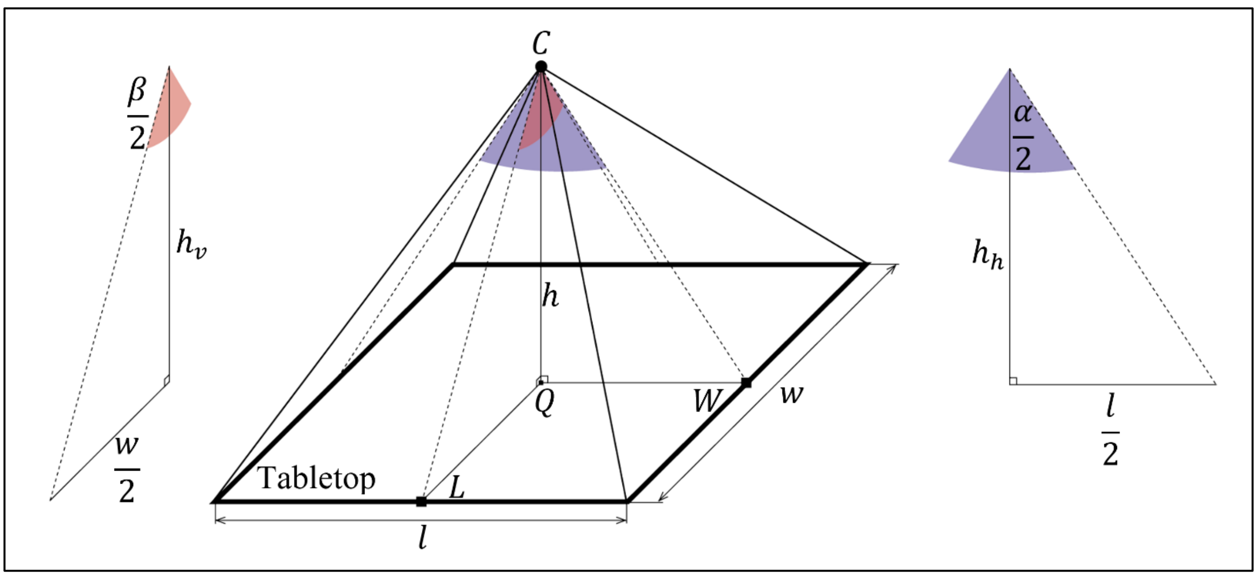


Figure 4.10 The geometric relationship of the camera view frustum and the tabletop represented in the cavalier projection.

Similarly, the minimum height h_v for the vertical field of view is

$$h_v = \frac{w}{2\tan\frac{\beta}{2}}$$

where α is the horizontal field of view and β the vertical field of view.

Thus, four results were solved which were based on horizontal field of view of color camera, vertical field of view of color camera, horizontal field of view of depth camera, and vertical field of view of depth camera, that is 2 feet and 7 inches (791.6 mm), 2 feet and 7 inches (791.53 mm), 3 feet and 4 inches (1008 mm), and 2 feet and 3 inches (695.42 mm) respectively. Theoretically, the greatest height among the four results can guarantee the full coverage of the tabletop for both color and depth camera. That is, the minimum height h of mounting the Kinect camera above the touchscreen tabletop surface is 3 feet and 4 inches (1008 mm).

However, in the practical scenario, the project model placed on the edge of the screen will immediately outside of the camera viewing frustum and nullified the measurement of these objects. This issue implies the Kinect sensor should be mounted higher to capture the actual height of these objects. Also, the exact height of installation depends on the model in the scene for the most height to the four extents.

Even if the models were to be placed above the center of the tabletop screen, the Kinect v2 camera has imposed a reliable minimum distance of 0.5 meter in the Microsoft official SDK documents which can be considered a near plane in the view frustum for getting a meaningful measurement to the closest end. The highest point of the model on the tabletop should not be higher than this near plane for accurate measurement or otherwise getting unreliable measurements.

4.4.4.4 Vertical Screen for Informative Assessment

- Name: Information Screen
- Description: A vertically installed screen dedicated to additional overall information about the site.
- Problem Statement: The physical models might occlude the tabletop screen.
- Context: Peripheral information that better be visualized vertically, such as street views and skyline view.
- Solution: Adding a vertical screen beside the tabletop.
- Rationale: The most direct approach to increase screen estate for additional information (such as reference documents, street views, and skylines) was to add another screen. This design also eliminated occlusion by the physical models.

- Examples: In this study, the two screens were assembled to become an ‘L-shape’ semi-enclosed space. The secondary 65-inch screen was mounted at a mobile stand vertically next to the tabletop, aligned to the tabletop screen. The skylines from four directions were displayed on this screen, depicted in figure 4.11 upper. This design avoided the duplicate entities of the 3D models during the interaction, so the users did not have to compare and confirm the changes between the physical model and the digital models constantly.
- Comments: The same scale should be used across two screens, so the users have consistent visual cues linking both screens. 3D views were generally unnecessary there because users could already see the tangible objects on the tabletop.

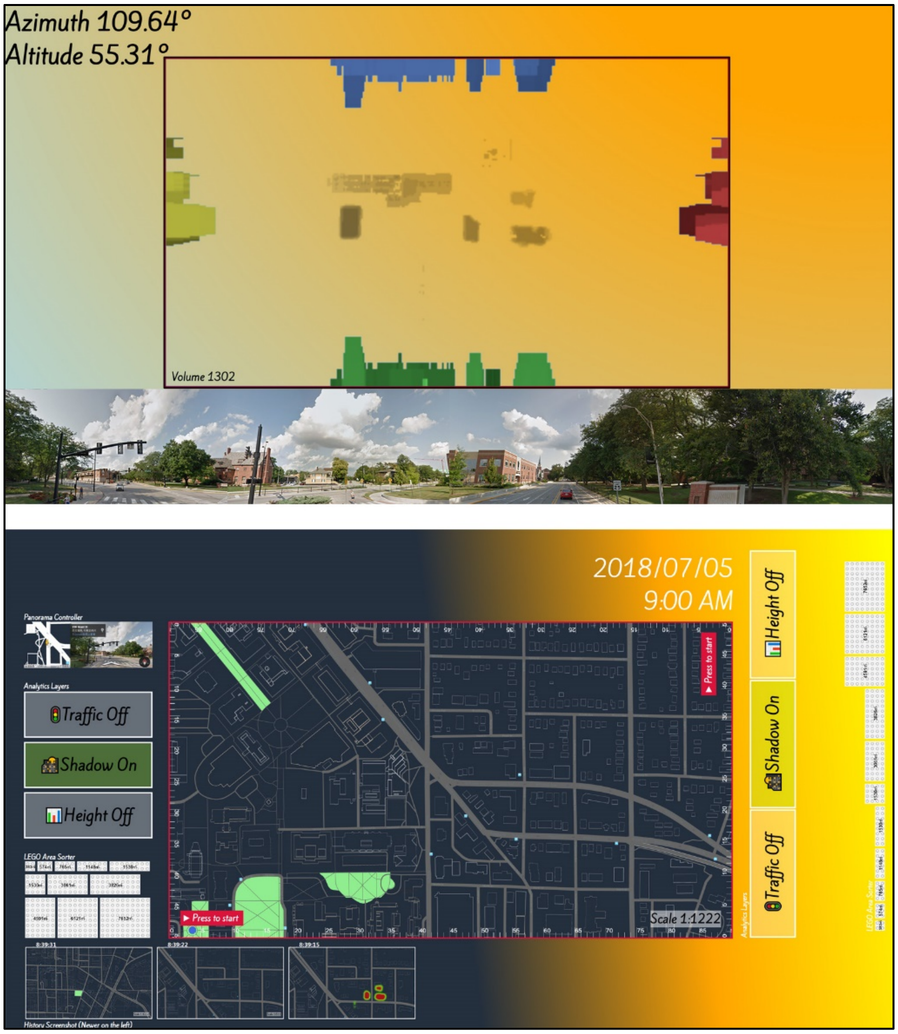


Figure 4.11 Upper: The interface of the information screen. The current information screen (the vertical screen) was showing the depth-cued skylines from four directions. Lower: The interface of the tabletop. The scale and design of the two screens were matched and consistent.

4.4.5 Software Deployment

Ideal software development and deployment environment for this application should be able to respond in real-time so that fast design iterations were possible. The easiness of using API and the extensibility of the online map services were the two important factors.

4.4.5.1 Web Application for Fast Iteration

- Name: Web Application
- Description: A type of system architecture implementation of the interface.

- Problem Statement: The typical system architecture deployment took too much time to develop and debug, especially when urban designers needed to alter some factors to work with a specific site situation.
- Context: Time is sensitive, and minor adjustment is required occasionally.
- Solution: The JavaScript library 'kinect2' (Verweirder, 2016) was used, running in the Node.js local server to retrieve the Kinect v2 camera depth frame data from the official Kinect v2 SDK for Windows to the web environment. Interaction and interface were running in the full-screen webpages. Two full-screen applications in separate browsers were created. The 'Broadcast Channel' API was used to keep the data between the two browsers on two screens in sync.
- Rationale: For a faster proof of concept, the development environment was set up on the web, so that on-the-fly debugging was not painful. The easy-to-develop web interface has been universally proved to be an 'easy-to-learn, easy-to-operate' interface for the users.
- Examples: The process of developing the system interface benefited from this web architecture. The improvement of the system interface can be made throughout the fast-developing iterations.
- Comments: There were trade-offs between easy development and system performance.

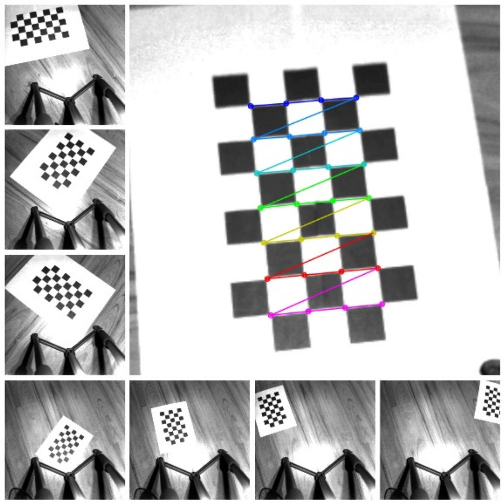
4.4.5.2 Image Pre-processing for Less Noise

- Name: Image Pre-processing
- Description: The process before the images is used for analyzing.
- Problem Statement: The amount of data generated from the sensor per second was large. Noise from the sensor stream was noticeable.
- Context: Optimal system performance is required.
- Solution: To avoid the optical radial and tangential aberration and associated expensive computing for the camera calibration, a safe zone of the depth frame was defined and cropped to use only the center pixels. The lowest value of the three frames of each depth pixel was used to suppress the random noise and to reduce data stream size.

- Rationale: The incoming depth image frames from the Kinect sensor streams were processed before use. A cleaner and lighter data stream can improve system performance in response time.
- Examples: For example, the side views (skyline) of the objects on the tabletop were calculated and transformed from the depth frame captured by the sensor. With less depth noise in the data stream, the users could easily see a neater skyline without bizarre flickering noise.
- Comments: There are trade-offs between resolution and system response time.

4.4.5.3 Depth Camera Calibration

- Name: Camera Calibration
- Description: The procedure to correct camera radial and tangential aberration.
- Problem Statement: The measurement result from the camera was unreliable if not properly calibrated.
- Context: The measurement of size and location of the physical model is from depth-sensing.
- Solution: Using a camera calibration software package, the intrinsic and extrinsic parameters can be retrieved for a specific camera. Reliable measurement can be calculated based on these parameters and coefficients.
- Rationale: Through camera calibration, the mapping relationship between the 3D world coordinates and the camera pixel coordinates is known. Therefore, the aberration of this particular camera is known, and an amendment can be applied to fix the aberration.
- Examples: Images used in the calibration process was demonstrated in figure 4.12. The extraction of the parameter of the camera in this study was done by GML C++ Camera Calibration Toolbox (Vezhnevets, Velizhev, Yakubenko, & Chetverikov, 2013).
- Comments: Based on the parameters, a more accurate measurement can be achieved. In this implementation, the depth calibration was discarded for better real-timeness.



Intrinsic Parameters

$$\begin{bmatrix} 424.510548 & 0 & 256.389048 \\ 0 & 418.697938 & 185.803191 \\ 0 & 0 & 1 \end{bmatrix}$$

Distortion Parameters

$$[0.164645 \quad -0.452904 \quad -0.002117 \quad 0.004700]$$

Figure 4.12 Left: The checkerboard images used for depth camera calibration in this study. Right: The intrinsic parameters and distortion coefficients retrieved from the tool.

4.4.5.4 Online Services for More Functionality

- Name: Online Services
- Description: Online software packages for more urban analysis.
- Problem Statement: The local system development could not reveal the status quo at the site.
- Context: The web deployment is used, and the internet is accessible.
- Solution: Google Maps and related APIs to draw shading, and traffic impact were implemented for demonstration in this study.
- Rationale: The online APIs provided an up-to-date map, terrain, and satellite information access and other extensibilities. The analytics or customized images overlays could be placed on top of the maps such as height heat map, shadow maps, historical maps, or master plan.
- Examples: In this study, Google Maps and APIs composited the central map of the tabletops. Because of the web development architecture, analytics modules and other online features such as local transit conditions were implemented without difficulties.
- Comments: Online analytics packages such as CityEngine or ArcGIS Online from Esri could also be plugged into the system.

4.5 Summary

This chapter answered the second research question by documenting the vital elements of the system components and constructing a list of primary elements within the three stages and four layers of the prototype interactive system. In the next chapter, the usability inspection of this prototype system was conducted.

CHAPTER 5. HEURISTIC EVALUATION

This chapter documented the process of heuristic evaluation, a method of usability inspection introduced in section 3.2.4 in answering the third research question. A set of heuristics for the prototype system was developed in the first place. Evaluating environments such as location, participants, sampling, and recruiting methods were also described in detail. The evaluation process was then introduced. After that, data collection, in conjunction with data analysis, was conducted at the same time for deeper insights into the research questions.

5.1 Defining Heuristics

The original list of heuristics (Nielsen & Molich, 1990) served as golden rules to inspect interface design. However, as technology advances, increased the complexity of interpersonal communication model, and the unique application to urban charrette scenario, those heuristics would be too broad, and some of the features that only exist in the new system could be overlooked. A more up-to-date version of the heuristic checklist was necessary to assess the system appropriately. Therefore, a new heuristics list incorporating the ten heuristics (Nielsen & Molich, 1990), Gerhardt-Powals' cognitive engineering principles (Gerhardt-Powals, 1996), UD Co-Spaces principles (Mahyar et al., 2016), as well as the goals of this study (i.e. tangible interoperability and multi-user capability) was developed for this study.

To assess whether the prototype system had addressed the three research questions, three corresponding main categories were chosen. These three categories focused on the collaborative environment in supporting easy communication for the general public. The new heuristics checklist consisted of three major categories: 'Usability', 'Multi-user Capability', and 'Tangibility' respectively. Seventeen sub-heuristics were describing detailed criteria among the main categories in various aspects. Detailed explanation or statement of each heuristic (design principles) together with assessment questions specific to the proposed system were asked, as shown in table 5.1. The participants of the heuristic evaluation, i.e., the evaluators, from different backgrounds and with different skill sets were then provided several columns to assess, rate, and comment on each specific sub-heuristic as they carried out the task on the tabletop. The evaluators were asked to record the feedback and encouraged to provided suggestions for the questions based on the heuristics.

Table 5.1 The heuristics evaluation checklist used in this study.

Heuristics Category	Sub-Heuristics Category	Heuristic Statements	Assessment Questions
Usability	Visibility of system status	The system should always keep users informed about what is going on, through appropriate feedback within a reasonable time.	Does the system show its current operation/status on the screen?
	Affordance	The system should speak the users' language, with words, phrases, and concepts familiar to the user, rather than system-oriented terms. Follow real-world conventions, making information appear in a natural and logical order.	Is it intuitive about what to do with the LEGO bricks and what analytics to expect on the screen?
	User control and freedom	Users often choose system functions by mistake and will need a clearly marked 'emergency exit' to leave the unwanted state without having to go through an extended dialogue. Support undo and redo.	Does the system support easy 'undo' functions back to the initial/original state?
	Consistency and standards	Users should not have to wonder whether different words, situations, or actions mean the same thing.	Is the system consistent in terms of function/status/analytics description?
	Error prevention	Even better than good error messages is a careful design which prevents a problem from occurring in the first place. Either eliminate error-prone conditions or check for them and present users with a confirmation option before they commit to the action.	Do you think the safe zone design (map area smaller than the screen) an appropriate design of preventing unwanted analytic results?
	Recognition rather than recall	Minimize the user's memory load by making objects, actions, and options visible. The user should not have to remember information from one part of the dialogue to another. Instructions for use of the system should be visible or easily retrievable whenever appropriate.	How do you find the usefulness of cross-screen solar position design in providing date and time references of current site situation?

Table 5.1 continued

Usability	Flexibility and efficiency of use	Accelerators — unseen by the novice user — may often speed up the interaction for the expert user such that the system can cater to both inexperienced and experienced users. Allow users to tailor frequent actions.	Does the interactive scale ruler at the map rim as well as the LEGO brick legend help speed up the task?
	Aesthetic and minimalist design	Dialogues should not contain information which is irrelevant or rarely needed. Every extra unit of information in a dialogue competes with the relevant units of information and diminishes their relative visibility.	Does the system user interface design follow the minimalist design principle both in tangible and digital components?
	Help users recognize, diagnose, and recover from errors	Error messages should be expressed in plain language (no codes), precisely indicate the problem, and constructively suggest a solution.	In case of error occurrence, does the system provide understandable language instead of computer science jargon or even codes?
	Help and documentation	Even though it is better if the system can be used without documentation, it may be necessary to provide help and documentation. Any such information should be easy to search, focused on the user's task, list concrete steps to be carried out, and not be too large.	Does the system provide help and documentation in guiding users' tasks in concrete steps?
Multi-user	Publicity and accessibility	The system setting is not exclusive to private users. The installation should be seen and accessible to all potential urban community members.	Does the system look multiple-user-friendly when someone is already engaging with the system?
	Attractiveness and engagement	The system design is unique for multi-user and appealing in appearance, so that the potential users may want to engage.	Do you find the system design unique for multi-user and appealing in appearance and be willing to participate?

Table 5.1 continued

Multi-user	Input and output simultaneity	The system design is not exclusive to a certain single user (e.g. the users who are operating the system). Using the system as well as the viewing of visualization outcome of the system can be done by multiple users at the same time.	Do you think the system can be used and viewed by multiple users at the same time?
	Normal lighting condition	The system should not be operatable only in a dark environment while reading paper-based documents and debating and discussing face-to-face are possible.	During the system operation, do you feel unnecessary to dim the light to read the screen?
Tangibility	Physical model recognition	Any change made in shape, location, the orientation of the physical model can be recognized by the system.	Does the system capture the shape, location, and orientation changes of the LEGO bricks?
	Real-timeness	Same as daily objects, the system should provide timely feedback according to users' tangible inputs.	Does the system response timely about the changes?
	Natural body interaction	Operating the system should not require carrying or wearing extra devices. The users can move freely while operating the system.	Do you feel it is okay to NOT equip any wearable device or tablet in order to operate the system successfully?

The evaluators were first asked to assess if the system met the criteria of the heuristic based on the assessment questions. Then, rated the problem on a scale based on Nielsen's severity rating scale (Nielsen & Molich, 1990):

- 0 - No Problem (No need to fix.)
- 1 - Cosmetic Problem (Problems can be worked around or neglected.)
- 2 - Minor Problem (Usability issues that need fixing.)
- 3 - Major Problem (Serious usability problem, consider a redesign.)
- 4 - Catastrophic Problem (Critical problem that must be completely redesigned.)

After that, recommendations or notes about this particular criterion was encouraged for insights into the research question. The evaluator was more than welcome to provide additional heuristics that might be overlooked by the form as at the bottom of figure 5.1.

Evaluator Field of Study		Date Rated	

Please note that the participation of this research is completely voluntary. You may choose not to participate or, if you agree to participate, You may skip the questions at any time.

Heuristic Evaluation on ShapeUD

Rating instruction
0 - No Problem
1 - Cosmetic Problem
2 - Minor Problem
3 - Major Problem
4 - Catastrophic Problem

Heuristics Category	Sub-Heuristics Category	Heuristic Statements	Assessment Questions	Pass (o) or Fail (×)	Severity (see above)	Recommendations/Note
Usability	Visibility of system status	The system should always keep users informed about what is going on, through appropriate feedback within reasonable time.	Does the system show its current operation/status on the screen?			
	Affordance	The system should speak the users' language, with words, phrases and concepts familiar to the user, rather than system-oriented terms. Follow real-world conventions, making information appear in a natural and logical order.	Is it intuitive about what to do with the LEGO blocks and what analytics to expect on the screen?			
	User control and freedom	Users often choose system functions by mistake and will need a clearly marked "emergency exit" to leave the unwanted state without having to go through an extended dialogue. Support undo and redo.	Does the system support easy 'undo' functions back to the initial/original state?			
	Consistency and standards	Users should not have to wonder whether different words, situations, or actions mean the same thing.	Is the system consistent in terms of function/status/analytics description?			
	Error prevention	Even better than good error messages is a careful design which prevents a problem from occurring in the first place. Either eliminate error-prone conditions or check for them and present users with a confirmation option before they commit to the action.	Do you think the safe zone design (map area smaller than the screen) an appropriate design of preventing unwanted analytic result?			
	Recognition rather than recall	Minimize the user's memory load by making objects, actions, and options visible. The user should not have to remember information from one part of the dialogue to another. Instructions for use of the system should be visible or easily retrievable whenever appropriate.	How do you find the usefulness of cross-screen solar position design in providing date and time references of current site situation?			
	Flexibility and efficiency of use	Accelerators — unseen by the novice user — may often speed up the interaction for the expert user such that the system can cater to both inexperienced and experienced users. Allow users to tailor frequent actions.	Does the interactive scale ruler at the map rim as well as the LEGO block legend help speed up the task?			
	Aesthetic and minimalist design	Dialogues should not contain information which is irrelevant or rarely needed. Every extra unit of information in a dialogue competes with the relevant units of information and diminishes their relative visibility.	Does the system user interface design follow the minimalist design principle both in tangible and digital compoments?			
	Help users recognize, diagnose, and recover from errors	Error messages should be expressed in plain language (no codes), precisely indicate the problem, and constructively suggest a solution.	In case of error occurance, does the system provide understandable language instead of computer science jargon or even codes?			
	Help and documentation	Even though it is better if the system can be used without documentation, it may be necessary to provide help and documentation. Any such information should be easy to search, focused on the user's task, list concrete steps to be carried out, and not be too large.	Does the system provide help and documentation in guiding users' task in concrete steps?			
Multi-user	Publicity and accessibility	The system setting is not exclusive to private users. The installation should be seen and accessible to all potential urban community members.	Does the system look multiple-user-friendly when someone is already engaging with the system?			
	Attractiveness and engagement	The system design is unique for multi-user and appealing in appearance, so that the potential users may want to engage.	Do you find the system design unique for multi-user and appealing in appearance and be willing to participate?			
	Input and output simultaneity	The system design is not exclusive to a certain single users (e.g. the users who are operating the system). Using the system as well as the viewing of visualization outcome of the system can be done by multiple users at the same time.	Do you think the system can be used and viewed by multiple users at the same time?			
	Normal lighting condition	The system should not be operatable only in dark environment, while reading paper-base documents and debating and discussing face-to-face are possible.	During the system operation, do you feel unnecessary to dim the light to read the screen?			
Tangibility	Physical model recognition	Any change made in shape, location, orientation of the physical model can be recognized by the system.	Does the system capture the shape, location, and orientation changes of the LEGO blocks?			
	Real-timeness	Same as daily objects, the system should provide timely feedbacks according to users' tangible inputs.	Does the system response timely about the changes?			
	Natural body interaction	Operating the system should not require carrying or wearing extra devices. The users can move freely while operating the system.	Do you feel it is okay to NOT equip any wearable device or tablets in order to successfully operate the system?			

Additional Comments (You are encouraged to provide comments which may not have been covered by the heuristics above.)	
1	
2	
3	
4	
5	

Figure 5.1 The heuristic evaluation checklist used in this study.

5.2 Evaluation Environment and Conditions

5.2.1 Location and Time

The current system prototype was located at the West Lafayette campus of Purdue University. The system was assembled and developed in the room 107 of Heavilon hall as shown in figure

5.2, at the location of iVIL lab, which a place primarily focuses on data visualization, user experience, tangible interaction, and immersive analytics researches.

Figure 5.2 The installation set up of the system prototype. The participants were surrounding the tabletop and relocating building blocks to test the changes of impact. The vertical screen was set to a satellite map for peripheral site reference.

Members from this lab were from the department of computer graphics technology in Purdue Polytechnic Institute. Background of the members included fields such as computer science, human-computer interaction, architectural design, urban design, industrial design, and new media. The interdisciplinary environment provided valuable early feedback on this qualitative research during the system development process. The heuristic evaluation was conducted during March 4, 2019 to March 21, 2019.

5.2.2 Participant

While a full scale, comprehensive usability testing was out of the scope of this study, the usability inspection presented in this research was intended to gather information about qualitative insights of what were the users' actual need, how they did it, and why they did it in this situation from small but experienced evaluators.

5.2.2.1 Population

This study intended to get insight into the design of the system and to make inferences about the population of adults currently living in the urbanized areas on the usability of the system. This broad group of people represented the closest target stakeholders who might have an interest in an urban design project. However, it was almost impossible to predict the availability and to portrait the characteristics of the actual users in a certain urban design charrette. The limitation has been addressed in section 3.3. Also, users' attitudes to what they need to know and how they express their opinions in an urban development project could also be largely depended on historical, geographical, political, ethnical, cultural context, or even individual preferences. The associated bias was inevitable and was aware of this research.

5.2.2.2 Sampling Method

The sampling strategy of this study, purposive sampling, is common in heuristic evaluation. The purposive sampling recruited evaluators with pre-selected criteria related to the research problem. Usually, the sample size of purposive sampling depends on the theoretical saturation, a condition when recruiting more evaluators could only bring marginal or little insights. As mentioned in section 3.2.4, a sample of five evaluators could discover over 80% of the design problem (Lewis, 2006; Turner, Lewis, & Nielsen, 2006; Virzi, 1992). Therefore, this study recruited five evaluators from five different fields.

5.2.3 Human Subjects Approval

The heuristic evaluation was an approach to assess the 'ShapeUD' interactive tabletop system by utilizing the data collected from human participants. When the study involves human participants, the activity falls into federal definitions of 'research and human subjects'. Therefore, to ensure the research was conducted ethically and in a manner that promoted the protection of the rights and welfare of human subjects, the research protocols must be reviewed by the Purdue University Institutional Review Board (IRB) according to the Human Research Protection Program (Purdue University, 2018).

5.2.3.1 The Approval of IRB Protocol

On December 21, 2018, the Purdue IRB determined that the study met the criteria for the 'Flex' Exemption Category (P100; Benign Behavioral Interventions) under U.S. Department of Health and Human Services Title 45 CFR 46 (Public Welfare).101(b). The email notification was attached with an 'Exemption Granted Notice' (See Appendix) re-addressing requirements both in general and in specific categories.

5.2.4 Recruitment and Selection Procedure of Participants

The recruitment was made by invitation emails or oral inquiry within the West Lafayette campus of Purdue University during February 2019. Volunteer participants replied to the email or consent by oral to express their interest in participating in the study. Screener questions such as study fields and prior familiarity of architectural/urban issues, experience using tangible interactive tabletops, and experience in usability testing were asked to determine the eligibility of the test. On the other hand, given the fact the West Lafayette's demographic composition being university personnel dominant, a university campus environment had advantages finding expert participants in diversified specialties. The schedule arrangements of the evaluators in the same lab were feasible.

A final list of five participants was selected in this research. All the participants had experience of at least one type of usability inspections before. Fields of study or professional affiliations included urban design, interaction design, computer science, new media, and industrial design. With such diverse background and skillsets, the consideration of these criteria for this study was to examine the system capability and compatibility to convey the design idea from the general public (especially from those professions not related to urban design fields) to the professional urban designers facing unfamiliar urban problems and situations.

5.2.5 Evaluation Process

According to the screener questions asked in the recruitment stage, the five participants had little experience operating interactive tabletops. It is necessary to give basic instruction on the use of tabletop before starting the evaluation.

Before the evaluation, the participants signed the research participant consent form, as stated in the previous section. The researcher spent about 15 minutes introducing the goal of the study, functions of the system, the elemental composition of the system hardware, and the emphasis of the heuristic evaluation with each participant. The use of LEGO bricks was demonstrated in how the system captures the change of the shape. The two simple tasks about reducing sun-dappled situation and alleviating traffic issues were introduced. The criteria for the heuristic evaluation checklist were briefly explained to the participants. The participants were encouraged to interact with the system to acquire familiarity.

During the task, the researcher observed the participants' behaviors on solving the tasks and made notes for further references. The two tasks took about 10 minutes on average. The researcher gave some hints when the participants were obviously stuck in a particular step or direct intervention when an application crash occurred.

After the tasks, the participants started to evaluate the system based on the criteria on the heuristic evaluation checklist. The participants could go back onto the system to repeat certain actions to verify heuristics. Upon finishing the heuristic evaluation checklist, the participants were interviewed about the experience of the system in addition to the written suggestions on the heuristic evaluation checklist. In the end, the heuristic evaluation checklists were collected for analysis.

5.3 Data Collection

The primary data collection methods of this study were observation, questionnaire (heuristic evaluation), and an interview with participants. The following section will describe the data collection procedures of these methods.

5.3.1 Observation

The observation was made during the tasks in usability inspection. The participant was assigned two tasks on the tabletop system. The participant was asked to follow the 'thinking aloud' protocol (Lewis, 1982) as they were interacting with the proposed tabletop system. In this way, the intention of a specific action and behavior was explicitly noticed by the researcher. The researcher took a non-intrusive stance during the tasks and remarked when the participants experience difficulties. The remark was later mentioned in the interview for more detail reasons.

5.3.2 Heuristic Evaluation

The feedback was recorded on the heuristic evaluation checklist. The participants were asked to assess the three major categories of heuristics in terms of usability, multi-user capability, and tangibility based on the experience of the tabletop system. Each of these three categories of heuristics consists of multiple sub-heuristics provided with a specific statement to be assessed. A more context-related system design question was raised for each single sub-heuristic about the prototype system so that the participants would not get lost in the vaguely described general criteria statement. The participants were asked to mark pass or fail for each sub-heuristic. In the case of not passing a particular sub-heuristic statement, the participants were further asked to rate the severity of this problem from cosmetic, minor, major, to catastrophic levels. Whether or not the heuristic was assessed as pass or fail, participants were provided a column for descriptive feedback or recommendation on improving the system. Beyond the existing heuristic statements, the participants were encouraged to explore new heuristic items that may not have been covered by the pre-set heuristics.

5.3.3 Interview

A short after-evaluation interview for each participant was conducted. The participants were asked about the overall experience of using the tabletop system. The heuristics were reviewed one by one for more open opinions and improvement suggestions. Remarks made during observation were reviewed for the reason behind. Additional recommendations were organized and categorized as new heuristics for future evaluations. As discussed in Chapter 2, these tangible-related issues would be difficult to explain and demonstrate in verbal and textual questionnaire records. Therefore, the participants were invited to sit close to the tabletop system and used drawings, diagrams, or LEGO bricks to express the system improvement ideas.

5.4 Data Analysis and Results

The data analysis was conducted after the completion of data collection. The data from the questionnaire was intended to get an assessment of the system design. Within each heuristic, the pros and cons could be visualized. The analysis of these qualitative data would include categorized and summarized best practices of modifiable tangible interactive system design, supported by descriptive behaviors across participants during the evaluation, as well as summative thinking from the author of this study. The overall and raw individual rating of the severity was visualized as in figure 5.3.

Heuristics Category	Sub-Heuristics Category	Severity	E1	E2	E3	E4	E5
			Raw Rating				
Usability	Visibility of system status	5%	1	0	0	0	0
	Affordance	10%	0	0	1	0	1
	User control and freedom	20%	1	0	2	0	1
	Consistency and standards	30%	1	2	1	0	2
	Error prevention	20%	1	1	1	0	1
	Recognition rather than recall	10%	1	1	0	0	0
	Flexibility and efficiency of use	10%	0	1	0	0	1
	Aesthetic and minimalist design	20%	1	0	2	0	1
	Help users recognize, diagnose, and recover from errors	25%	1	3	0	0	1
	Help and documentation	55%	3	3	3	1	1
Multi-user	Publicity and accessibility	5%	1	0	0	0	0
	Attractiveness and engagement	20%	2	1	0	0	1
	Input and output simultaneity	15%	1	0	2	0	0
	Normal lighting condition	20%	1	1	2	0	0
Tangibility	Physical model recognition	20%	0	2	2	0	0
	Real-timeness	10%	0	0	1	0	1
	Natural body interaction	5%	1	0	0	0	0

Figure 5.3 The overview of heuristic evaluation. Severity rating means were converted to percentages. Raw severity rating was provided on the right for each evaluator from E1 to E5. The darker the red shade indicated the more severity.

5.4.1 Detailed Feedback on Heuristics

In the usability category, the feedback was aggregated as below:

5.4.1.1 Visibility of System Status

Heuristic statement: The system should always keep users informed about what is going on, through appropriate feedback within a reasonable time.

The corresponding assessment question was as follows:

Does the system show its current operation/status on the screen?

The written feedback collected from this question was (were):

- Satisfactory. No other recommendation.
- Can place a title on the screen to indicate the current site project. As this will be the most outstanding sign from far away.

5.4.1.2 Affordance

Heuristic statement: The system should speak the users' language, with words, phrases, and concepts familiar to the user, rather than system-oriented terms. Follow real-world conventions, making information appear in a natural and logical order.

The corresponding assessment question was as follows:
Is it intuitive about what to do with the LEGO bricks and what analytics to expect on the screen?

The written feedback collected from this question was (were):

- The 3D LEGO blocks gave an immediate understanding of the 3D urban space layout.
- The traffic indicated by lines were too trivial to notice when the LEGO bricks were modified. Should exaggerate the analytics.
- The LEGO bricks can be dismantled and reassembled easily.

5.4.1.3 User Control and Freedom

Heuristic statement: Users often choose system functions by mistake and will need a clearly marked 'emergency exit' to leave the unwanted state without having to go through an extended dialogue. Support undo and redo.

The corresponding assessment question was as follows:
Does the system support easy 'undo' functions back to the initial/original state?
The system can be easily reset by reloading the webpage. No undo functions are needed.

The written feedback collected from this question was (were):

- Adding a refresh button on the interface would be an improvement.
- It was not easy to remember how I assembled my LEGO. Should have a mechanism to record this physical part.

5.4.1.4 Consistency and Standards

Heuristic statement: Users should not have to wonder whether different words, situations, or actions mean the same thing.

The corresponding assessment question was as follows:
Is the system consistent in terms of function/status/analytics description?

The written feedback collected from this question was (were):

- On the vertical screen, the four projections of the skyline were unclear. At first glance, the meaning of color-coded bars was confusing. The mapping relation between the LEGO bricks and the four elevation graphs were not immediately understandable. Adding labels such as ‘east elevation’ and ‘south elevation’ are necessary.
- There is some consistency issue between the two screens.

5.4.1.5 Error Prevention

Heuristic statement: Even better than good error message is a careful design which prevents a problem from occurring in the first place. Either eliminate error-prone conditions or check for them and present users with a confirmation option before they commit to the action.

The corresponding assessment question was as follows:
Do you think the safe zone design (map area smaller than the screen) an appropriate design of preventing unwanted analytic results?

The written feedback collected from this question was (were):

- Although the rim setbacks were considerate, they were also a waste of the screen estate. There was no need for such a large space.
- The history snapshot area can be hidden when not needed.
- A collapsible toggle panel is suggested when the buttons are not in use. More interactive design for the menus would enable more functions.
- An interactive full-screen mode for the map would be more useful.

5.4.1.6 Recognition Rather than Recall

Heuristic statement: Minimize the user’s memory load by making objects, actions, and options visible. The user should not have to remember information from one part of the dialogue to another. Instructions for use of the system should be visible or easily retrievable whenever appropriate.

The corresponding assessment question was as follows:
How do you find the usefulness of cross-screen solar position design in providing date and time references of current site situation?

The written feedback collected from this question was (were):

- It was helpful when the system set up indoor or operated at night.
- The Sun position on the two screens was very helpful in knowing where did the shadows from.
- Need more plain language about this solar simulation. 'Azimuth' is too professional.
- A miniature of the Sun hemisphere visualization can help clarify this simulation.

5.4.1.7 Flexibility and Efficiency of Use

Heuristic statement: Accelerators — unseen by the novice user — may often speed up the interaction for the expert user such that the system can cater to both inexperienced and experienced users. Allow users to tailor frequent actions.

The corresponding assessment question was as follows:
Does the interactive scale ruler at the map rim as well as the LEGO brick legend help speed up the task?

The written feedback collected from this question was (were):

- The area sorter was very useful.
- The ruler should be multiplied by the current scale to be useful.
- The ruler somehow seemed useless, but the area sorter was handy.
- The ruler was not easy to use in its current state.
- The ruler on the rim should be slidable and make thorough crosshair guidelines to be measurable.

5.4.1.8 Aesthetic and Minimalist Design

Heuristic statement: Dialogues should not contain information which is irrelevant or rarely needed. Every extra unit of information in a dialogue competes with the relevant units of information and diminishes their relative visibility.

The corresponding assessment question was as follows:
Does the system user interface design follow the minimalist design principle both in tangible and digital components?

The written feedback collected from this question was (were):

- The interface design was simple and clear.
- It might be a good idea to group (use a group rectangle) and color-coded the functions on the screen.

5.4.1.9 Help Users Recognize, Diagnose, and Recover from Errors

Heuristic statement: Error messages should be expressed in plain language (no codes), precisely indicate the problem, and constructively suggest a solution.

The corresponding assessment question was as follows:
In case of error occurrence, does the system provide understandable language instead of computer science jargon or even codes?

The written feedback collected from this question was (were):

- The system was easy to use and fool-proof, so no error was encountered.
- The system should also take RGB photos from the camera to record the trial and error of the urban designs.
- So far, there was no error.

5.4.1.10 Help and Documentation

Heuristic statement: Even though it is better if the system can be used without documentation, it may be necessary to provide help and documentation. Any such information should be easy to search, focused on the user's task, list concrete steps to be carried out, and not be too large.

The corresponding assessment question was as follows:
Does the system provide help and documentation in guiding users' tasks in concrete steps?

The written feedback collected from this question was (were):

- Documentation is not necessary for this system since it was self-explanatory. However, it is good to have one if an exception happens.
- Only oral introduction from the coordinator. No written documentation provided.

In the multi-user category, the feedback was aggregated as below:

5.4.1.11 Publicity and Accessibility

Heuristic statement: The system setting is not exclusive to private users. The installation should be seen and accessible to all potential urban community members.

The corresponding assessment question was as follows:
Does the system look multiple-user-friendly when someone is already engaging with the system?

The written feedback collected from this question was (were):

- The UI has different directions layout, which is suitable for supporting multiple users.
- There was enough space for multiple users at the same time.

5.4.1.12 Attractiveness and Engagement

Heuristic statement: The system design is unique for multi-user and appealing in appearance, so that the potential users may want to engage.

The corresponding assessment question was as follows:
Do you find the system design unique for multi-user and appealing in appearance and be willing to participate?

The written feedback collected from this question was (were):

- The system was useful and fun.
- It lowers the threshold of discussing urban issues. I feel relaxed to make several attempts.
- The 'pegman' dial was not working as expected.
- A real object (the 'pegman' dial) would be more intuitive than the current street view controller design. (Note from the researcher: The 'pegman' dial was not working properly and was removed in the later evaluations. Therefore, the 'pegman' was not presented for this evaluator.)
- There was still inequality that biased to the users on the longer side of the tabletop.
- In some cases, the LEGO blocks were way too small in scale, which made the system less appealing.

5.4.1.13 Input and Output Simultaneity

Heuristic statement: The system design is not exclusive to a certain single user (e.g. the users who are operating the system). Using the system as well as the viewing of visualization outcome of the system can be done by multiple users at the same time.

The corresponding assessment question was as follows:
Do you think the system can be used and viewed by multiple users at the same time?

The written feedback collected from this question was (were):

- For the current design, the system can support at least two users at the same time. However, if more than four users, the tabletop seemed croweded.
- It would be better if the control panel can be 'generated' into multiple copies and draggable at the convenience of all the directions of users. Such as a plus sign (+) to increase one more panel and press the minus sign (-) to delete an existing panel.

5.4.1.14 Normal Lighting Condition

Heuristic statement: The system should not be operable only in a dark environment, while reading paper-based documents and debating and discussing face-to-face are possible.

The corresponding assessment question was as follows:
During the system operation, do you feel unnecessary to dim the light to read the screen?

The written feedback collected from this question was (were):

- No special lighting condition was required. It was natural to use the system.
- There was some reflection from the ceiling light. I could not see clearly what was on the screen on the other side.
- After suggesting dimming the light a little bit, the contents on the screen of the tabletop turned out to be more appealing together with the LEGO blocks.

In the tangibility category, the feedback was aggregated as below:

5.4.1.15 Physical Model Recognition

Heuristic statement: Any change made in shape, location, the orientation of the physical model can be recognized by the system.

The corresponding assessment question was as follows:
Does the system capture the shape, location, and orientation changes of the LEGO bricks?

The written feedback collected from this question was (were):

- The system simulated the changes of the LEGO bricks. However, the outline smoothness of shadows can be improved.
- The accuracy of capturing the LEGO blocks movement still needs to be improved.

5.4.1.16 Real-timeness

Heuristic statement: Same as daily objects, the system should provide timely feedback according to users' tangible inputs.

The corresponding assessment question was as follows:
Does the system response timely about the changes?

The written feedback collected from this question was (were):

- The system performed in real-time very well, no lagging occurs.
- The LEGO bricks and the system support real-time interactions.

5.4.1.17 Natural Body Interaction

Heuristic statement: Operating the system should not require carrying or wearing extra devices. The users can move freely while operating the system.

The corresponding assessment question was as follows:
Do you feel it is okay to NOT equip any wearable device or tablet in order to successfully operate the system?

The written feedback collected from this question was (were):

- The system is self-consistent and contains all the functions it claimed.
- It was OK to use the system without other equipment.
- Minor problems in sensing accuracy.

Other heuristics were organized and categorized as follows. During the interview, the participants were encouraged to provide open opinions that may not have been covered by the heuristics above. Although the evaluators did not provide the name of newly added heuristics, the comments could be categorized into the following aspects: system architecture, situation awareness, annotation system, and other off-system topics discussions.

5.4.1.18 System Architecture

- Implement the system in a different framework like C# WPF as the native Kinect SDK provided so that the system can include more computer vision features and improve overall performance. So far, the web app implementation was challenging to perform intensive image-processing features.

5.4.1.19 Situation Awareness

- The information about the road closure and division during the construction may also be visualized as the urban design changes.
- I would like to see a 3D rendering embedded into the street view.
- Although extra wearable devices are not necessary, a VR simulation about the future vision of the construction from street level perspective will be beneficial for an ordinary citizen to imagine how the future will look like.
- The shadow simulation was most useful when a projection of the shades can be visualized on the surface of the LEGO blocks so that the solar condition of a specific balcony window can be verified.

5.4.1.20 Annotation System

- Need a mechanism to designate different types of buildings such as housing, schools, or hospitals as they generate a different volume of traffics.
- Better have a label or a sticker on top of the LEGO blocks to recognize different buildings.

5.4.1.21 Off-system Topics

- Can consider incorporating social network service (SNS) to share various design solutions. This should help to extend the discussion afterward away from the system.
- The system somehow oversimplified the problem. Sometimes the devil is in the details. The system should allow more delicate tangible pieces to reveal those details.

5.5 Summary

This chapter presented the detailed process of heuristic evaluation: establishing heuristics, preparing evaluation environment and recruiting evaluators, collecting data, analyzing results, and summarizing suggestions. This heuristic evaluation answered the third research question about the effectiveness of the prototype tangible interactive system on supporting charrette-like collaborative urban design activities.

Based on the results in this chapter, the following chapters discussed the future direction of system design and concluded the study in general.

CHAPTER 6. DISCUSSION

This chapter discussed the advantages, contribution, and limitations of the prototype system based on the literature, feedback during development, and results from the heuristic evaluation.

6.1 Advantages of the Prototype System

Compared to the previous systems, the prototype system in this study addressed the following pitfalls stated in section 4.1:

- Inflexible (unmovable and/or unmodifiable) Tangibles. The modifiable tangible - LEGO bricks used in the prototype system support the arbitrary design from the users. This pixelated feature released the imagination of design possibilities and thus, enriched the design. Also, the LEGO bricks were considered universally low threshold in operation. The result from the evaluation showed it was a favorable choice that could provoke curiosity and therefore, encourage participation. This feature was important as urban development discussion often impeded by the inflexible, finished product-like physical models that better left the work to the professionals. The toy-like appearance of LEGO bricks created a more relax and tolerant atmosphere for the discussion. This added capability of interoperability in the proposed system proved to be an effective approach to increase involvement.
- Lacking Volume Awareness. The use of a depth sensor in the prototype system was able to detect the 3-dimensional shape and provided more freedom in urban design activities. Comparing to the previous systems, the depth awareness gave the prototype system a new dimension the same as we had in the real world. The use of modifiable tangible – LEGO bricks was natural with depth-sensing technology. This coupling usage proved to have a good affordance according to the results, as novice users of the tangible interactive system do not have to learn specialized skills in order to participate in the design and discussion.
- Pre-set Design Alternatives. The combined use of depth-sensing and LEGO also extended the limited number of design alternatives and supported the creation of a new design solution on-the-fly. The modifiable LEGO bricks could effectively accelerate

design iterations in the process as a new design alternative could be converted from a previous design in an incremental style. These elements greatly expanded the possibilities of design exploration and reduced the time to make the model.

- Coarse Resolution. The Kinect v2 camera used in this study was the ToF depth sensor with one of the highest resolutions in the mass market that enabled LEGO detection. The use of depth-sensing technology gave meaning to the appearance and the shape of the tangible models. The design on the tabletop system was no longer a symbolic or an abstract geometric token but a concrete miniature of the building mass. Changes of LEGO bricks could be captured by the system and ultimately revealed in the urban analytics.
- Projection Occlusion. Removing the projectors from the system also removed the occlusion of image projections by the objects or by the users themselves. Confusion about the shadow created by occlusion was eliminated. This system set up had more benefits other than occlusion.
- Operable Only in the Dark. The dual-screen solution made it easy to read paper-based urban design documents and other work such as modifying the model in normal room lighting. This allowed more natural activities when introducing the interactive system into the charrettes.
- Exclusive to a Single User. No VR/MR equipment was used in this system. Considering the design solution was to present to the general public, it was important to make sure everyone informative in sync. This set up also alleviated the concerns about screen door effects and nausea and dizziness when using the system.

The development process of the ShapeUD system also established a reusable element manifesto for building a tangible interactive tabletop for urban design charrette scenario. The system elements were organized into four layers: hardware configuration, software environment, screen interface design, and tangible interaction design. A three-stage system pipeline: 3D reconstruction, processing and analysis, and visualization, orchestrated and integrated the elements towards an immersive analytics environment. By adding the modifiable tangible input, the urban design ideas could be effectively and efficiently delivered in the discussion, especially for non-professionally trained users' groups within a limited time frame.

The ShapeUD tabletop created a more relax and tolerant atmosphere for the urban issue discussion. The multi-orientation design not only provided a venue for casual gathering that triggers face-to-face discussion but also became a new type of installation attracting many potential users before the real engagement began. The added layer of interoperability in the participatory design activity proved to be a good interface to invite passers-by and increase involvement.

The ShapeUD tabletop could effectively accelerate design iterations in the participatory design process by verifiable simulated interferences. The importance of real-timeness could not be emphasized enough as people expected an immediate sensory response as they interacted with a physical object in daily life.

6.2 Contribution to the Community

The contributions of this study to the extant literature were as follows:

- Discovering Direction - Reviewed and discussed the challenges, opportunities, and future trends of a real-time, constructible, and tangible interactive tabletop system interface and interaction design in a smart city context. A trend of using more quantity and higher granularity of tangible models was found.
- Centering Tangibility – According to the rationale of embodied interaction in the existing literature, the researcher identified the pivotal role of the tangible medium in the system for immersive analytics during the urban design charrette that previous systems often overlooked. A new system design principle ‘tangible interoperability’ was considered the utmost importance in this scenario. The use of modifiable tangible models was confirmed beneficial to understand and express.
- Implementing Prototype - Developed a functioning interactive system prototype supported by consumer-grade hardware and LEGO bricks that were conveniently accessible. Interactive analytic modules about shading areas and traffic pressure were demonstrated and evaluated in the usability inspection.
- Documenting Elements - Summarized the best practices for system design in building the element manifesto, so the solution developed in this study can be reused, adapted, and generalized in a recurring situation.

6.3 Limitations of the Result

While most of the evaluators appreciated the novelty and attractiveness of this kind of tangible system, some of the problems emerged. The heuristic evaluation revealed better results in the category ‘Multi-user’ and category ‘Tangibility’ but less satisfactory in the category ‘Usability’. The nature of tangibility using physical models had some conflict in speed and amount of ‘generating’ larger context of peripheral environments. The analytics of design sometimes required a community context to make correct judgments. The need for context means in order to get a more accurate result, and the users had to also build the surrounding buildings (which sometimes implies much extra work) besides the target site. The prototype could not support a virtual peripheral feature in the current set up.

According to the result from the heuristic evaluation, consistency between the tangible elements and digital elements interface, and the affordance of the system required more in-depth consideration. The topography and other much more complicated spatial structure were not supported in the original system design. This deficiency made it less realistic in a real-world charrette situation. A possible solution would be using transparent terrain models.

The proxemic of this kind of hybrid interactive tabletop system was still not thoroughly examined due to the evaluation condition. This also resulted from a lack of help and documentation and less ideal affordance of the system. The interpersonal interaction on this kind of interactive tabletop was still underexplored. Future work may need more exploration of the interpersonal communication mechanism in this modifiable tangible setting.

Some other issues made the prototype system less than ideal when used in a real-world charrette situation. For the current ShapeUD system, it was mostly limited by the resolutions of the Kinect v2 depth sensors. To make space for touch screen controls, to reduce perspective distortion, and to accelerate system response time, only a small portion of the depth-sensing pixels was used, and minimal calibration was applied. Most of the operation was limited to an approximately 16mm depth precision. This issue affected the detection of some structures, such as slope rooftops. Moreover, there was rarely a better depth sensor available in the market by the time this research was conducted that could work in this close-range condition in both high resolution and high precision. Given time, a better depth sensor will be available in the future, and better measurement can be expected in volume detection.

Another issue was only the top surface of the physical objects were detected. This issue limited the system from detecting more complicated structures. While this system was enough for the majority of the urban design projects, some design features were not aware including overhanging structures and other facade variations (such as a void throughout the building from the side). For the building features like this, two or more depth sensors from different angles are needed. However, the multiple sensors would bring in more system design complexity and other complication, such as occlusions, moving mechanics, 3D point cloud alignment problems, as well as participating users' proxemics with such installation.

CHAPTER 7. CONCLUSION

This chapter concluded the paper by recapitulating the goal, research questions, major processes, significant findings, and contributions of this research.

The main goal of this research was to design, build, and evaluate an interactive system for stakeholders in urban design charrette that facilitates effective and efficient communication.

The following three research questions were asked to achieve the goal:

1. What were the current problems of interactive systems in the urban design charrette?
2. How to support aiding stakeholders in urban design charrette that allows easy communication, input, and modification of the design?
3. How effective was the prototype tangible interactive system on user interaction in charrette-like collaborative urban design activities?

For the first research question, related literature was reviewed in the following topics: increasing urban population, ICT-enabled smart city, participatory urban design in the community, cognitive benefits of embodied interaction, depth-sensing technologies, and previous system designs.

The literature review established the context that the future urban development would be on a new scale and new capacity. A broad range of stakeholders was already or about to enter the public consultation activities for their interests and ready for co-design exploration proactively. Nevertheless, the inefficiency of communication during the urban design charrette was observed by the researcher based on career experience and verified by these researches on tabletops in the literature. The review then turned to the support of theories in searching for a solution addressing low efficiency of communication during the urban charrettes: embodied interaction, a tangible tool but with ICT age enhancement. Hybrid models preserved sensory quality while adding informative interactions. Previous researches of systems leveraging these merits were reviewed and analyzed, which provided useful inspirations about system design and real-world use cases. The timeline of interactive tabletops revealed that the tangible objects were becoming the centerpiece on these kinds of interactive tabletops. Users of the system could express their ideas and get interactive information by directly modifying physical models. This transformation, in turn, encourages more stakeholders to engage in participatory urban design. However, to become a successful communication tool in the urban design charrette, the tangible model needed some extent of modularized flexibility. The LEGO and the feasibility to use on the interactive tabletop was thus investigated. To ensure accuracy in detecting LEGO bricks, the critical component, the depth sensor, as well as its calibration methods, were reviewed in detail.

The existing interactive systems had revealed several issues, as follows:

- Lacking Volume Awareness.
- Inflexible (unmovable and/or unmodifiable) Tangibles.
- Pre-set Design Alternatives.
- Coarse Resolution.
- Projection Occlusion.
- Operable Only in the Dark.
- Exclusive to a Single User.

Based on these issues and existing embodied interaction theories, a new system design principle 'tangible interoperability' was considered the utmost importance for the prototype system in this study.

For the second research question, a prototype system was then implemented based on the design principles according to the existing literature and researches, as well as the added 'tangible interoperability'. A manifesto of elements, specifically addressing the problems that existed in the previous systems, from rationale, to usage condition, to implementation example, were documented.

For the third research question, the prototype system was assessed using the heuristic evaluation method through five experienced evaluators from five different fields. The feedback was positive and promising. High assessments came from categories such as easiness to check analytics, multi-user friendly, and natural interaction. On the other hand, based on the comments, there was still room for improvement in documentation and map ruler design.

In sum, the contributions of this study to the extant literature were:

- Discovering Direction,
- Centering Tangibility,
- Implementing Prototype,
- Documenting Elements.

During the development of the ShapeUD, the researcher received valuable and insightful suggestions from professors, colleagues, students, and friends from various backgrounds and expertise. Many of these suggestions were critical for avoiding some system design errors in the early stages. The ShapeUD system research presented a possibility of implementing a modifiable tangible input into an interactive tabletop for urban design charrettes. This prototype system verified the concept of using hybrid objects in collaborative design scenarios or spatiotemporal related activities such as resource allocation and policy clarification. Future paradigm shifts might happen, bringing in more groundbreaking and exciting changes. Until then, continuous discussions are needed in this fast-changing world of technology.

APPENDIX A. IRB SUBMISSION

The following section described the documents submitted to the Purdue University Institutional Review Board. The submitted protocol package included the cover page, the application narrative form, the research participant consent form, and the questionnaire (the heuristic evaluation checklist).

The cover page indicated the type of submission as a new application narrative of project 'ShapeUD: A Real-time, Modifiable, Tangible Interactive Tabletop System for Collaborative Urban Design', together with other necessary information including point of contact of the principal investigator about the project.

The application narrative form described the proposed research rationale, specific step-by-step procedures to follow of the study, types of data to be collected, inclusion and exclusion criteria for the subjects, subject recruitment process, compensation procedures, confidentiality precautions, also possible risks to subjects, and further benefits to be gained by the individual and/or society. The narrative also needs the investigator's evaluation of the risk-benefit ratio and other documental issues in detail.

The research participant consent form introduced the participants to the critical information of the study. Voluntary participation was emphasized at the very beginning. The consent form also provided detailed descriptions and explanations about the purpose, procedure, duration, possible risks or discomforts, potential benefits, incentive, confidentiality precautions, rights, and hotline/mail/email contact of the research. The participants must sign the consent form before taking part in the study and may choose not to participate at any time during without penalty or loss of benefits that were otherwise entitled.

The questionnaire, i.e., the 'Heuristic Evaluation Checklist', was an assessment tool of human interface design that was consolidated principles from multiple sources based on the long history of usability research, cognitive psychology, and design best practices (Nielsen & Molich, 1990; Gerhardt-Powals, 1996; Shneiderman et al., 2016). Participants were asked to rate the heuristic statements in both pass/fail and severity score form. The pass/fail rating determined whether a particular heuristic statement was fulfilled, whereas the severity score quantified the unsatisfactory level. Recommendations on each sub heuristics category were also collected.

There are six categories of research that are exempt from IRB review according to the federal regulations. However, this research did not fit the criteria for exemption as the IRB description (Purdue University, 2018). This IRB protocol was then filed as non-exempt research. The IRB protocol was submitted via the online portal of Office of the Executive Vice President for Research and Partnerships and confirmed receipt by the email notification from Purdue IRB office on December 12, 2018. The IRB protocol submission was supplied with an ID number 1812021434 for further tracking purposes.

APPENDIX B. IRB EXEMPTION GRANTED NOTICE

Exemption Granted Notice received from Purdue University Institutional Review Board.

PURDUE
UNIVERSITY

HUMAN RESEARCH PROTECTION PROGRAM
INSTITUTIONAL REVIEW BOARDS

To:	CHEN, YINGJIE
From:	DICLEMENTI, JEANNIE D, Chair Social Science IRB
Date:	12/21/2018
Committee Action:(P100)	Determined Exempt, Category **(P100)**
IRB Action Date:	12 / 21 / 2018
IRB Protocol #:	1812021434
Study Title:	ShapeUD: A Real-time, Modifiable, Tangible Interactive Tabletop System for Collaborative Urban Design

The Institutional Review Board (IRB) has reviewed the above-referenced study application and has determined that it meets the criteria for exemption under 45 CFR 46.101(b).

Before making changes to the study procedures, please submit an Amendment to ensure that the regulatory status of the study has not changed. Changes in key research personnel should also be submitted to the IRB through an amendment.

General

- To recruit from Purdue University classrooms, the instructor and all others associated with conduct of the course (e.g., teaching assistants) must not be present during announcement of the research opportunity or any recruitment activity. This may be accomplished by announcing, in advance, that class will either start later than usual or end earlier than usual so this activity may occur. It should be emphasized that attendance at the announcement and recruitment are voluntary and the student's attendance and enrollment decision will not be shared with those administering the course.
- If students earn extra credit towards their course grade through participation in a research project conducted by someone other than the course instructor(s), such as in the example above, the students participation should only be shared with the course instructor(s) at the end of the semester. Additionally, instructors who allow extra credit to be earned through participation in research must also provide an opportunity for students to earn comparable extra credit through a non-research activity requiring an amount of time and effort comparable to the research option.
- When conducting human subjects research at a non-Purdue college/university, investigators are urged to contact that institution's IRB to determine requirements for conducting research at that institution.
- When human subjects research will be conducted in schools or places of business, investigators must obtain written permission from an appropriate authority within the organization. If the written permission was not submitted with the study application at the time of IRB review (e.g., the school would not issue the letter without proof of IRB approval, etc.), the investigator must submit the

written permission to the IRB prior to engaging in the research activities (e.g., recruitment, study procedures, etc.). Submit this documentation as an FYI through Coeus. This is an institutional requirement.

Categories 2 and 3

- Surveys and questionnaires should indicate
  - only participants 18 years of age and over are eligible to participate in the research; and
  - that participation is voluntary; and
  - that any questions may be skipped; and
  - include the investigator's name and contact information.
- Investigators should explain to participants the amount of time required to participate. Additionally, they should explain to participants how confidentiality will be maintained or if it will not be maintained.
- When conducting focus group research, investigators cannot guarantee that all participants in the focus group will maintain the confidentiality of other group participants. The investigator should make participants aware of this potential for breach of confidentiality.

Category 6

- Surveys and data collection instruments should note that participation is voluntary.
- Surveys and data collection instruments should note that participants may skip any questions.
- When taste testing foods which are highly allergenic (e.g., peanuts, milk, etc.) investigators should disclose the possibility of a reaction to potential subjects.

You are required to retain a copy of this letter for your records. We appreciate your commitment towards ensuring the ethical conduct of human subjects research and wish you luck with your study.

REFERENCES

Ahlers, D., Driscoll, P., Löfström, E., Krogstie, J., & Wyckmans, A. (2016, April). Understanding smart cities as social machines. In *Proceedings of the 25th International Conference Companion on World Wide Web* (pp. 759-764). International World Wide Web Conferences Steering Committee.

Albino, V., Berardi, U., & Dangelico, R. M. (2015). Smart cities: Definitions, dimensions, performance, and initiatives. *Journal of Urban Technology, 22*(1), 3-21.

Aldawood, S., Aleissa, F., Almalki, A., Alrashed, T., Alhindi, T., Alnasser, R., ... & Al-Wabi, A. (2015, August). Collaborative Tangible Interface (CoTI) for Complex Decision Support Systems. In *International Conference of Design, User Experience, and Usability* (pp. 415-424). Springer, Cham.

Alizadeh, T. (2017). Urban Digital Strategies: Planning in the Face of Information Technology?. *Journal of Urban Technology*, *24*(2), 35-49.

Anderson, K. (2019, March 25). Singapore Changi Airport caught using Microsoft Kinect sensors. Retrieved from https://www.onmsft.com/news/singapore-changi-airport-caught-using-microsoft-kinect-sensors

Arnstein, S. R. (1969). A ladder of citizen participation. *Journal of the American Institute of planners*, *35*(4), 216-224.

Balcetis, E., & Dunning, D. (2007). Cognitive dissonance and the perception of natural environments. *Psychological Science*, *18*(10), 917-921.

Barzaghi, R. & Pinto, L. (2014). *Elementi di topografia e trattamento delle osservazioni [Elements of topography and treatment of observations]* (pp. 1–416). Milano, Italy: Città Studi Edizioni.

BBC. (2018, March 6). *Lego admits it made too many bricks*. Retrieved from https://www.bbc.com/news/business-43298897

Bekkering, H., & Neggers, S. F. (2002). Visual search is modulated by action intentions. *Psychological science*, *13*(4), 370-374.

Ben-Joseph, E., Ishii, H., Underkoffler, J., Piper, B., & Yeung, L. (2001). Urban simulation and the luminous planning table: Bridging the gap between the digital and the tangible. *Journal of planning education and research*, *21*(2), 196-203.

Borghi, A. M., & Cimatti, F. (2010). Embodied cognition and beyond: Acting and sensing the body. *Neuropsychologia*, *48*(3), 763-773.

Bouguet, J. Y. (2000). *Matlab camera calibration toolbox.* Caltech Technical Report.

Brignull, H., & Rogers, Y. (2003, September). Enticing people to interact with large public displays in public spaces. In *Proceedings of INTERACT* (Vol. 3, pp. 17-24).

Breuer, T., Bodensteiner, C., & Arens, M. (2014, October). Low-cost commodity depth sensor comparison and accuracy analysis. In *SPIE Security+ Defence* (pp. 92500G-92500G). International Society for Optics and Photonics.

Brown, D. C. (1966). Decentering distortion of lenses. *Photogrammetric Engineering and Remote Sensing, 32*(3), 444-462.

Chandler, P., & Sweller, J. (1991). Cognitive load theory and the format of instruction. *Cognition and instruction*, *8*(4), 293-332.

Chow, J. C., & Lichti, D. D. (2013). Photogrammetric bundle adjustment with self-calibration of the PrimeSense 3D camera technology: Microsoft Kinect. *IEEE Access, 1*, 465-474.

Cilliers, E. J., & Timmermans, W. (2014). The importance of creative participatory planning in the public place-making process. *Environment and Planning B: Planning and Design*, *41*(3), 413-429.

Claes, S., & Moere, A. V. (2015, June). The role of tangible interaction in exploring information on public visualization displays. In *Proceedings of the 4th International Symposium on Pervasive Displays* (pp. 201-207). ACM.

Cleveland, W. S., & McGill, R. (1985). Graphical perception and graphical methods for analyzing scientific data. *Science*, *229*(4716), 828-833.

Cooper, A. (2018, December 10). *Groundbreaking study examines effects of screen time on kids*. Retrieved from https://www.cbsnews.com/news/groundbreaking-study-examines-effects-of-screen-time-on-kids-60-minutes/?ftag=CNM-00-10aab7e&linkId=60800971

Corti, A., Giancola, S., Mainetti, G., & Sala, R. (2016). A metrological characterization of the Kinect V2 time-of-flight camera. *Robotics and Autonomous Systems, 75*, 584-594.

Dalsgaard, P., & Halskov, K. (2012, October). Tangible 3D tabletops: combining tangible tabletop interaction and 3D projection. In *Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design* (pp. 109-118). ACM.

Darwish, W., Tang, S., Li, W., & Chen, W. (2017). A New Calibration Method for Commercial RGB-D Sensors. *Sensors, 17*(6), 1204.

Davoodianidaliki, M., & Saadatseresht, M. (2013, September). Calibrate kinect to use in computer vision, simplified and precise. In *Machine Vision and Image Processing (MVIP), 2013 8th Iranian Conference on* (pp. 310-314). IEEE.

Design Council. (2018, April 11). The Design Process: What is the Double Diamond? Retrieved from https://www.designcouncil.org.uk/news-opinion/design-process-what-double-diamond

Fonseca, D., Valls, F., Redondo, E., & Villagrasa, S. (2016). Informal interactions in 3D education: Citizenship participation and assessment of virtual urban proposals. *Computers in Human Behavior*, *55*, 504-518.

Fryer, J. G. (1989). Camera calibration in non-topographic photogrammetry. *Handbook of Non Topographic Photogrammetry, American Society of Photogrammetry and Remote Sensing, 2*, 51-69.

Fuchs, S., & Hirzinger, G. (2008, June). Extrinsic and depth calibration of ToF-cameras. In *Computer Vision and Pattern Recognition, 2008. CVPR 2008. IEEE Conference on* (pp. 1-6). IEEE.

Gerhardt-Powals, J. (1996). Cognitive engineering principles for enhancing human-computer performance. *International Journal of Human-Computer Interaction, 8*(2), 189-211.

Giffinger, R., & Gudrun, H. (2010). Smart cities ranking: an effective instrument for the positioning of the cities?. *ACE: Architecture, City and Environment, 4*(12), 7-26.

Gokturk, S. B., Yalcin, H., & Bamji, C. (2004, June). A time-of-flight depth sensor-system description, issues and solutions. In *Computer Vision and Pattern Recognition Workshop, 2004. CVPRW'04. Conference on* (pp. 35-35). IEEE.

Graf, H., Santos, P., & Stork, A. (2010, April). Augmented reality framework supporting conceptual urban planning and enhancing the awareness for environmental impact. In *Proceedings of the 2010 Spring Simulation Multiconference* (p. 181). Society for Computer Simulation International.

Gudmundsson, S. A., Aanæs, H., & Larsen, R. (2007, July). Environmental effects on measurement uncertainties of time-of-flight cameras. In *2007 International Symposium on Signals, Circuits and Systems* (Vol. 1, pp. 1-4). IEEE.

Gui, P., Ye, Q., Chen, H., Zhang, T., & Yang, C. (2014, June). Accurately calibrate kinect sensor using indoor control field. In *Earth Observation and Remote Sensing Applications (EORSA), 2014 3rd International Workshop on* (pp. 9-13). IEEE.

Guillemin, P., & Friess, P. (2009). Internet of things strategic research roadmap. *The Cluster of European Research Projects, Tech. Rep.*

Haggag, H., Hossny, M., Filippidis, D., Creighton, D., Nahavandi, S., & Puri, V. (2013, December). Measuring depth accuracy in RGBD cameras. In *Signal Processing and Communication Systems (ICSPCS), 2013 7th International Conference on* (pp. 1-7). IEEE.

Häkkilä, J., Koskenranta, O., Posti, M., & He, Y. (2014, February). City landmark as an interactive installation: experiences with stone, water and public space. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction* (pp. 221-224). ACM.

Halatsch, J. (2007, July). Value lab: Collaboration in space. In *Information Visualization, 2007. IV'07. 11th International Conference* (pp. 376-381). IEEE.

Hall, E. T. (1963). A system for the notation of proxemic behavior1. *American anthropologist, 65*(5), 1003-1026.

Hansard, M., Horaud, R., Amat, M., & Evangelidis, G. (2014). Automatic detection of calibration grids in time-of-flight images. *Computer Vision and Image Understanding, 121*, 108-118.

Haring, R., Ogawa, H., Lindinger, C., Hörtner, H., Afshar, S., & Stolarsky, D. (2010, October). The city at hand: media installations as urban information systems. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries* (pp. 667-670). ACM.

Hartley, R., & Zisserman, A. (2004). *Multiple View Geometry in Computer Vision.* Cambridge: Cambridge University Press. doi:10.1017/CBO9780511811685

Heikkila, J., & Silven, O. (1997). A four-step camera calibration procedure with implicit image correction. In *Computer Vision and Pattern Recognition, 1997. Proceedings., 1997 IEEE Computer Society Conference on* (pp. 1106-1112). IEEE.

Herrera, D., Kannala, J., & Heikkilä, J. (2012). Joint depth and color camera calibration with distortion correction. *IEEE Transactions on Pattern Analysis and Machine Intelligence, 34*(10), 2058-2064.

Houghton, K., Miller, E., & Foth, M. (2014). Integrating ICT into the planning process: impacts, opportunities and challenges. *Australian Planner*, *51*(1), 24-33.

Hurlbert, M., & Gupta, J. (2015). The split ladder of participation: a diagnostic, strategic, and evaluation tool to assess when participation is necessary. *Environmental Science & Policy*, *50*, 100-113.

Ideum. (2016). Platform Classic Multi-touch Table - Integrated, Interactive Touch | Ideum. Retrieved from https://ideum.com/products/touch-tables/platform-classic?id=65

Ishii, H., Ben-Joseph, E., Underkoffler, J., Yeung, L., Chak, D., Kanji, Z., & Piper, B. (2002, September). Augmented urban planning workbench: overlaying drawings, physical models and digital simulation. In *Proceedings of the 1st International Symposium on Mixed and Augmented Reality* (p. 203). IEEE Computer Society.

Jin, J., Gubbi, J., Marusic, S., & Palaniswami, M. (2014). An information framework for creating a smart city through internet of things. *IEEE Internet of Things Journal, 1*(2), 112-121.

Ju, Z., Wang, Y., Zeng, W., Chen, S., & Liu, H. (2013, July). Depth and RGB image alignment for hand gesture segmentation using Kinect. In *Machine Learning and Cybernetics (ICMLC), 2013 International Conference on* (Vol. 2, pp. 913-919). IEEE.

Jung, J., Lee, J. Y., Jeong, Y., & Kweon, I. S. (2015). Time-of-flight sensor calibration for a color and depth camera pair. *IEEE transactions on pattern analysis and machine intelligence, 37*(7), 1501-1513.

Kahlmann, T., Remondino, F., & Ingensand, H. (2006). Calibration for increased accuracy of the range imaging camera swissrangertm. *Image Engineering and Vision Metrology (IEVM), 36*(3), 136-141.

Kim, J. H., Choi, J. S., & Koo, B. K. (2013, October). Calibration of multi-Kinect and multi-camera setup for full 3D reconstruction. In *Robotics (ISR), 2013 44th International Symposium on* (pp. 1-5). IEEE.

Kim, Y. S., Kang, B., Lim, H., Choi, O., Lee, K., Kim, J. D., & Kim, C. (2012). Parametric model-based noise reduction for ToF depth sensors. *Three-Dimensional Image Processing (3DIP) and Applications, II*. doi: 10.1117/12.907614

Lachat, E., Macher, H., Landes, T., & Grussenmeyer, P. (2015). Assessment and calibration of a RGB-D camera (Kinect v2 Sensor) towards a potential use for close-range 3D modeling. *Remote Sensing, 7*(10), 13070-13097.

Lachat, E., Macher, H., Mittet, M. A., Landes, T., & Grussenmeyer, P. (2015). First experiences with Kinect v2 sensor for close range 3D modelling. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, 40*(5), 93.

Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. University of Chicago press.

Lefloch, D., Nair, R., Lenzen, F., Schäfer, H., Streeter, L. V., Cree, M. J., ... & Kolb, A. (2013, September). Technical Foundation and Calibration Methods for Time-of-Flight Cameras. In *Time-of-Flight and Depth Imaging* (pp. 3-24).

The LEGO Group. (2017, October 17). *The LEGO history*. Retrieved from https://www.lego.com/en-us/aboutus/lego-group/the_lego_history

Lenzen, F., Kim, K. I., Schäfer, H., Nair, R., Meister, S., Becker, F., ... & Theobalt, C. (2013). Denoising strategies for time-of-flight data. In *Time-of-Flight and Depth Imaging. Sensors, Algorithms, and Applications* (pp. 25-45). Springer Berlin Heidelberg.

Lewis, C. (1982). Using the 'thinking-aloud' method in cognitive interface design. *Research Report RC9265, IBM TJ Watson Research Center*.

Lewis, J. R. (2006). Sample sizes for usability tests. *Interactions, 13*(6), 29.

Lin, T. H., Liu, C. H., Tsai, M. H., & Kang, S. C. (2014). Using augmented reality in a multiscreen environment for construction discussion. *Journal of Computing in Civil Engineering*, *29*(6), 04014088.

Lindner, M., & Kolb, A. (2006). Lateral and depth calibration of PMD-distance sensors. *Advances in Visual Computing*, 524-533.

Lindner, M., Schiller, I., Kolb, A., & Koch, R. (2010). Time-of-flight sensor calibration for accurate range sensing. *Computer Vision and Image Understanding, 114*(12), 1318-1328.

Liu, W., Fan, Y., Zhong, Z., & Lei, T. (2012, July). A new method for calibrating depth and color camera pair based on kinect. In *Audio, Language and Image Processing (ICALIP), 2012 International Conference on* (pp. 212-217). IEEE.

Macknojia, R., Chávez-Aragón, A., Payeur, P., & Laganière, R. (2013, January). Calibration of a network of kinect sensors for robotic inspection over a large workspace. In *Robot Vision (WORV), 2013 IEEE Workshop on* (pp. 184-190). IEEE.

Mahyar, N., Burke, K. J., Xiang, J. E., Meng, S. C., Booth, K. S., Girling, C. L., & Kellett, R. W. (2016, November). UD Co-Spaces: A Table-Centred Multi-Display Environment for Public Engagement in Urban Design Charrettes. In *Proceedings of the 2016 ACM on Interactive Surfaces and Spaces* (pp. 109-118). ACM.

Maquil, V., Psik, T., & Wagner, I. (2008, February). The ColorTable: a design story. In *Proceedings of the 2nd international conference on Tangible and embedded interaction* (pp. 97-104). ACM.

Memarovic, N., Gehring, S., & Fischer, P. T. (2015). ELSI Model: Bridging user engagement around interactive public displays and media facades in urban spaces. *Journal of Urban Technology, 22*(1), 113-131.

Microsoft Docs. (2014). WindowsPreview.Kinect Namespace. Retrieved from https://docs.microsoft.com/en-us/previous-versions/windows/kinect/dn758774%28v%3dieb.10%29

Milgram, P., Takemura, H., Utsumi, A., & Kishino, F. (1995, December). Augmented reality: A class of displays on the reality-virtuality continuum. In *Telemanipulator and telepresence technologies* (Vol. 2351, pp. 282-293). International Society for Optics and Photonics.

Mittet, M. A., Grussenmeyer, P., Landes, T., Yang, Y., & Bernard, N. (2013, May). Mobile outdoor relative localization using calibrated RGB-D cameras. In *Proceedings of the 8th International Symposium on Mobile Mapping Technology, Tainan, Taiwan* (pp. 1-3).

Mueller, J., Lu, H., Chirkin, A., Klein, B., & Schmitt, G. (2018). Citizen Design Science: A strategy for crowd-creative urban design. *Cities*, *72*, 181-188.

Münster, S., Georgi, C., Heijne, K., Klamert, K., Noennig, J. R., Pump, M., ... & van der Meer, H. (2017). How to involve inhabitants in urban design planning by using digital tools? An overview on a state of the art, key challenges and promising approaches. *Procedia Computer Science*, *112*, 2391-2405.

Murphy, G. L., & Wright, J. C. (1984). Changes in conceptual structure with expertise: Differences between real-world experts and novices. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *10*(1), 144.

Nam, T., & Pardo, T. A. (2011, June). Conceptualizing smart city with dimensions of technology, people, and institutions. In *Proceedings of the 12th annual international digital government research conference: digital government innovation in challenging times* (pp. 282-291). ACM.

Neirotti, P., De Marco, A., Cagliano, A. C., Mangano, G., & Scorrano, F. (2014). Current trends in Smart City initiatives: Some stylised facts. *Cities, 38*, 25-36.

Nielsen, J., & Molich, R. (1990, March). Heuristic evaluation of user interfaces. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 249-256). ACM.

Nuojua, J., Juustila, A., Räisänen, T., Kuutti, K., & Soudunsaari, L. (2008, October). Exploring web-based participation methods for urban planning. In *Proceedings of the Tenth Anniversary Conference on Participatory Design 2008* (pp. 274-277). Indiana University.

Oksman, V., Väätänen, A., & Ylikauppila, M. (2014). Co-creation of sustainable smart cities. Users, participation and service design. In *8th International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies, UBICOMM 2014* (pp. 189-195). International Academy, Research, and Industry Association IARIA.

Pagliari, D., & Pinto, L. (2015). Calibration of kinect for xbox one and comparison between the two generations of microsoft sensors. *Sensors, 15*(11), 27569-27589.

Perera, C., Zaslavsky, A., Christen, P., & Georgakopoulos, D. (2014). Sensing as a service model for smart cities supported by internet of things. *Transactions on Emerging Telecommunications Technologies, 25*(1), 81-93.

Petrasova, A., Harmon, B., Petras, V., & Mitasova, H. (2014, June). GIS-based environmental modeling with tangible interaction and dynamic visualization. In *Proceedings of the 7th International Congress on Environmental Modelling and Software, San Diego, CA, USA* (pp. 15-19).

Portman, M. E., Natapov, A., & Fisher-Gewirtzman, D. (2015). To go where no man has gone before: Virtual reality in architecture, landscape architecture and environmental planning. *Computers, Environment and Urban Systems, 54*, 376-384.

Prescott, B., & McLean, G. F. (1997). Line-based correction of radial lens distortion. *Graphical Models and Image Processing, 59*(1), 39-47.

Purdue University. (2018). Human Research Protection Program. Retrieved from https://www.irb.purdue.edu/index.php

Raposo, C., Barreto, J. P., & Nunes, U. (2013, June). Fast and accurate calibration of a kinect sensor. In *3DTV-Conference, 2013 International Conference on* (pp. 342-349). IEEE.

Roggema, R., Martin, J., Remnant, M., Alday, G., & Mansfield, P. (2014). Design charrettes in two days: Sea Lake and Bendigo. In *The Design Charrette* (pp. 117-149). Springer, Dordrecht.

Salim, F. (2014, April). Tangible 3D urban simulation table. In *Proceedings of the Symposium on Simulation for Architecture & Urban Design* (p. 23). Society for Computer Simulation International.

Sareika, M., & Schmalstieg, D. (2010, May). Bimanual handheld mixed reality interfaces for urban planning. In *Proceedings of the International Conference on Advanced Visual Interfaces* (pp. 189-196). ACM.

Schaffers, H., Komninos, N., Pallot, M., Trousse, B., Nilsson, M., & Oliveira, A. (2011). Smart cities and the future internet: Towards cooperation frameworks for open innovation. *The future internet*, 431-446.

Schiller, I., Beder, C., & Koch, R. (2008). Calibration of a PMD-camera using a planar calibration pattern together with a multi-camera setup. *The international archives of the photogrammetry, remote sensing and spatial information sciences, 21*, 297-302.

Scott, C. L., Harris, R. J., & Rothe, A. R. (2001). Embodied cognition through improvisation improves memory for a dramatic monologue. *Discourse Processes*, *31*(3), 293-305.

Shibo, L., & Qing, Z. (2012). A new approach to calibrate range image and color image from Kinect. In *Intelligent Human-Machine Systems and Cybernetics (IHMSC), 2012 4th International Conference on* (Vol. 2, pp. 252-255). IEEE.

Shneiderman, B., Plaisant, C., Cohen, M., Jacobs, S., Elmqvist, N., & Diakopoulos, N. (2016). *Designing the user interface: strategies for effective human-computer interaction*. Pearson.

Skulmowski, A., Pradel, S., Kühnert, T., Brunnett, G., & Rey, G. D. (2016). Embodied learning using a tangible user interface: The effects of haptic perception and selective pointing on a spatial learning task. *Computers & Education*, *92*, 64-75.

Steinberger, F., Foth, M., & Alt, F. (2014, June). Vote with your feet: Local community polling on urban screens. In *Proceedings of The International Symposium on Pervasive Displays* (p. 44). ACM.

Swaminathan, R., & Nayar, S. K. (1999). Non-metric calibration of wide-angle lenses and polycameras. In *Proceedings. 1999 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (Cat. No PR00149)* (Vol. 2, pp. 413-419). IEEE.

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive science*, *12*(2), 257-285.

Sweller, J., Van Merrienboer, J. J., & Paas, F. G. (1998). Cognitive architecture and instructional design. *Educational psychology review*, *10*(3), 251-296.

Thiel, S. K., Reisinger, M., Röderer, K., & Fröhlich, P. (2016). Playing (with) democracy: A review of gamified participation approaches. *JeDEM-eJournal of eDemocracy and Open Government*, *8*(3), 32-60.

Triggs, B., McLauchlan, P. F., Hartley, R. I., & Fitzgibbon, A. W. (1999, September). Bundle adjustment—a modern synthesis. In *International workshop on vision algorithms* (pp. 298-372). Springer, Berlin, Heidelberg.

Turner, C. W., Lewis, J. R., & Nielsen, J. (2006). Determining usability test sample size. *International encyclopedia of ergonomics and human factors, 3*(2), 3084-3088.

Tversky, B., & Hard, B. M. (2009). Embodied and disembodied cognition: Spatial perspective-taking. *Cognition*, *110*(1), 124-129.

United Nations, Department of Economic and Social Affairs, Population Division (2015). *World Urbanization Prospects: The 2014 Revision, (ST/ESA/SER.A/366).*

Van Assche, K., Beunen, R., Duineveld, M., & de Jong, H. (2013). Co-evolutions of planning and design: Risks and benefits of design perspectives in planning systems. *Planning Theory*, 12(2), 177-198.

Vermeulen, J., Luyten, K., Coninx, K., & Marquardt, N. (2014). Addressing Challenges in Crowded Proxemics-Aware Installations. ACM.

Verweirder, W. (2016). Node-kinect2. Retrieved from https://github.com/wouterverweirder/kinect2

Vezhnevets, V., Velizhev, A., Yakubenko, A., & Chetverikov, N. (2013). GML C++ Camera Calibration Toolbox. Retrieved from http://graphics.cs.msu.ru/en/node/909

Virzi, R. A. (1992). Refining the test phase of usability evaluation: How many subjects is enough?. *Human factors, 34*(4), 457-468.

Wagner, I., Basile, M., Ehrenstrasser, L., Maquil, V., Terrin, J. J., & Wagner, M. (2009, June). Supporting community engagement in the city: urban planning in the MR-tent. In *Proceedings of the fourth international conference on Communities and technologies* (pp. 185-194). ACM.

Wang, K., Zhang, G., & Bao, H. (2014). Robust 3D reconstruction with an RGB-D camera. *IEEE Transactions on Image Processing, 23*(11), 4893-4906.

Wang, Y. T., Shen, C. A., & Yang, J. S. (2014). Calibrated Kinect sensors for robot simultaneous localization and mapping. In *Methods and Models in Automation and Robotics (MMAR), 2014 19th International Conference on* (pp. 560-565). IEEE.

Wasenmüller, O., & Stricker, D. (2016, November). Comparison of kinect v1 and v2 depth images in terms of accuracy and precision. In *Asian Conference on Computer Vision* (pp. 34-45). Springer, Cham.

Whittemore, R., Chase, S. K., & Mandle, C. L. (2001). Validity in qualitative research. *Qualitative health research, 11*(4), 522-537.

Yang, L., Zhang, L., Dong, H., Alelaiwi, A., & El Saddik, A. (2015). Evaluating and improving the depth accuracy of Kinect for Windows v2. *IEEE Sensors Journal, 15*(8), 4275-4285.

Yamazoe, H., Habe, H., Mitsugami, I., & Yagi, Y. (2012, November). Easy depth sensor calibration. In *Pattern Recognition (ICPR), 2012 21st International Conference on* (pp. 465-468). IEEE.

Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, M. (2014). Internet of things for smart cities. *IEEE Internet of Things journal, 1*(1), 22-32.

Zhang, C., & Zhang, Z. (2014). Calibration between depth and color sensors for commodity depth cameras. In *Computer Vision and Machine Learning with RGB-D Sensors* (pp. 47-64). Springer International Publishing.

Zhang, Z. (2000). A flexible new technique for camera calibration. *IEEE Transactions on pattern analysis and machine intelligence, 22*(11), 1330-1334.

Zheng, Y., Capra, L., Wolfson, O., & Yang, H. (2014). Urban computing: concepts, methodologies, and applications. *ACM Transactions on Intelligent Systems and Technology (TIST), 5*(3), 38.