Chapter 2
Developing the eXtended Tangible User Interface as an Experimental Platform for Geo CPS

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Abstract Geotechnology, including GIS, remote sensing, and GNSS, is finding many applications in disaster risk reduction. Information flows in conventional systems tend to be one-way, however, from the physical world to cyber world, and their effectiveness often depends on professional training while support for participation is weak. This chapter overviews the history of the concept of the tangible user interface (TUI), which intuitively bridges GIS content in the cyber world onto a "tangible table," a mock-up of the physical world for intuitive communication. After examining the common features of TUIs, we extend the concepts to recent applications in cyber-physical systems (CPSs) in the geographic dimension. We show how a Geo CPS platform (a CPS spatialized in the geographic world) with eXtended TUI (XTUI) can enhance the integration of information within cyber, physical and social spaces as well as the interactions among them in the application context. The system architecture and functions of Geo CPS with XTUI are constructed to reflect intuitive interactions of sensing, process and actuation (iSPA). Finally, we present a community trial at the Urban Living Lab in Yokohama City and discuss the potential for the Geo CPS platform with XTUI for disaster risk reduction.

Keywords Tangible user interface · CPS · GIS · Participation · ISPA

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2.1 Introduction

Geotechnology, a collective term that these days include geographic information systems (GIS), remote sensing (RS), and the Global Navigation and Service Systems (GNSS), is often applied in the area of disaster risk reduction. These three technologies all emerged in the 1960s, grew in the 1970s and 1980s, boomed in the 1990s, and developed further in the 2000s. For more than half a century, geotechnology has steadily evolved and established niches in various combinations in the spectrum of modern information technology. GNSS, started with the Global Positioning System (GPS) in the USA, has transformed positioning and become part of the infrastructure of human daily life and services; remote sensing gives us a periodic bird's eye view of the planet surface at low cost and with high performance; GIS can manage a huge amount of spatial data and is commonly used in various applications from daily life to business; participatory decision systems supported by GIS can engage communities in preparing for, organizing relief from, and managing reconstruction after disasters. The three technologies complement each other to form an informational chain for sensing in the physical world, processing in the computational cyber world, and visualizing by the user community in society. Geotechnology has been seen as one of the frontiers in the twenty-first century along with nanotechnology and biotechnology (Gewin 2004).

Disaster risk reduction (DRR) has benefited substantially from geotechnology in terms of sensing/monitoring, modeling/analyzing, and visualization/presentation (Ghapar et al. 2018). However, traditional geotechnology solutions were generally built on closed-system conditions with stand-alone or centralized computational architectures. Data transactions were siloed, requiring time to cooperate across sectors and sites. Sophisticated uses of geospatial systems often require intensive training for operation and data interpretation. User interfaces were typically confined to several input devices for operators and lacked the appeal needed to attract general users.

The proliferation of mobile devices and the Internet of Things (IoT) are bringing about change; however, location-aware devices can continuously track when, where, and how people and objects appear and move. From there it becomes possible to learn behaviors and extrapolate trends, to consider what was there previously, and to predict what might happen next (Bosch 2018). By integrating with IoT, geotechnology is enabled to not only collect geospatial data in the physical world and manage it in the cyber world but also to actuate tangible objects in real time. For instance, driverless vehicles can move around in the midst of complex road conditions. Drones can take off and land anytime, anyplace, and collect and process images in real time. These systems exemplify a new type of sensing and mapping technology—a cyber-physical system (CPS)—in which data and information interact across *cyber and physical worlds* quickly and seamlessly.

CPS along with IoT is considered one of the most promising technologies for Industry 4.0 and Society 5.0. It has been studied in engineering and applied in manufacturing, civil construction, and utility management, etc. and has emerged quickly in market applications, such as drone surveillance, driverless vehicles, robotic services, and so on. However, the term and concept of CPS have not yet been widely accepted in the geographic dimension. To have completely driverless vehicles operating on public roads, much intensive experimentation is needed. Communication gaps exist between developers, engineers, and users. The development of solutions has generally been a one-way process flowing from engineers to clients, which has less flexibility for user interaction and lacks methods for solving social issues in an open geographic environment. We know that "one size does not fit all" in open conditions, particularly in disaster risk reduction, which requires fine accuracy of data, high speed system responses in harsh natural conditions, and much cooperation with the public. Interactive platforms that bring together complex natural and social conditions are constantly being sought.

Regarding interaction and user communication, a unique approach has been explored by using a tangible user interface (TUI) (Ishii et al. 2004; Maquil et al. 2015; Petrasova et al. 2018; White and Ross 1984). TUI is a technique to mock up a physical space on a 2D, 2.5D, or 3D landscape table by using augmented reality. The key concept of TUI is to bridge the cyber and physical worlds in a tangible way for multiple users to participate simultaneously in discussions. The idea of TUI has been evolved with tangible bits (Ishii and Ullmer 1997), message bricks (Fitzmaurice et al. 1995), a dynamic terrain machine, and recently with "Tangible Landscapes" where a physical space can be mocked up by illuminating clay, plasticine, or sand (Petrasova et al. 2018) and GIS data in cyber space are projected onto the 3D mock-up by map projection. Modifications of the landscape in clay and sand can be captured with a gesture camera, processed, and projected back onto the landscape table.

Although TUI is powerful for use in presentation and communication, its applications are currently largely limited to demonstration and education. On the other hand, CPS and TUI share the idea of linking the cyber and physical worlds. CPS aims to work directly in the real world while TUI mocks up the physical space for social communications. This commonality shows the potential for us to combine their advantages by extending TUI for CPS, making the "black box" of the processing in CPS visible for user communication. We believe that linking CPS and TUI will help to explore a new style of system development and practice in information technology and social communication.

Therefore, this chapter proposes the eXtended Tangible User Interface (XTUI) for a CPS platform in the geographic dimension by connecting sensing, processing, actuation, and social interaction in cyber–physical–social worlds. Our idea is to extend TUI for co-designing CPS solutions in a participatory way by bridging cyber, physical, and social worlds in a physically shared space for group discussion. The system can be used as a platform for education in environmental and disaster management, or as a tool for technical training with GIS and CPS, or as a testbed for business solutions in a specific social context. In the following sections, we will first review the history of TUI and CPS trends. We will then introduce the concept of XTUI and system architecture for the Geo CPS platform. Finally, we will discuss the potential of XTUI for participatory disaster risk reduction.

2.2 History of TUI

TUI was originally an inspiration by Durrell Bishop in his graduate project at the Royal College of Art in 1992 (Petrasova 2015). Users could place a message ball at the designated points of a machine to receive and actuate messages. This could be considered the first experiment of IoT, making a physical space integrated with conceptual workings by a platform and a moveable device. Based on this idea, Ishii and Buxton introduced a concept of graspable user interfaces or “bricks” in 1995, an interface to control electronic or virtual objects on an ActiveDesk (Fitzmaurice et al. 1995). ActiveDesk is a large display surface on which the message “bricks” could be moved around and actuate responses. Since then, TUI has evolved continuously in terms of three issues: how to make the ActiveDesk tangible, how to enrich the contents of the table, and how to establish communications between the physical table and the cyber world.

In the early stage, efforts went toward the ActiveDesk. The first idea was the “tangible bits,” which allow users to “grasp & manipulate” bits in the center of users’ attention by coupling the bits with daily physical objects and architectural surfaces (Ishii and Ullmer 1997). It could be considered to be one of the origins of cyber–physical systems though the accuracy was limited to the size of bits. Underkoffler and Ishii (1999) set up a system dubbed “Urp” to cast light shadows on a physical architectural model for urban planning. This could be considered as one of the original examples of map projection.

A utopia of full interaction and communication between tangible table and cyber space was an experiment at Mitsubishi Electric Research Laboratories by the invention of the Diamond Touch Table (DTT) in 2001, and later under license to Circle Twelve Inc. in 2008. It is a multi-touch, interactive PC interface device that has the capability of allowing multiple persons to interact simultaneously while identifying which person is touching where. Profile recognition through radio frequency identification (RFID) is used in the system. Before the user approaches the system, the user information is gathered, stored in a database, and coupled to a RFID tag, which is part of the badge provided. When the user moves toward the model the person’s profile is recognized and a selection of datasets will be automatically created based upon the profile information. This could be considered to be a pioneer of cyber–physical interactive communication systems with IoT in a laboratory setting for multiple users.

With ActiveDesk, a table can be equipped with a touchable 2D screen. A team in the Netherlands led by Alessandra Scotta developed a prototype multi-user touchable user interface (MUTI) in the form of a tangible table on which map layers and objects appear as buttons and icons. MUTI involves much more than touch-sensitive interface screens or whiteboards shaped like tables (Hofstra et al. 2008). In contrast to the DTT, this system does not “remember” what is drawn by whom. Participants did not see the flat screen table with buttons as being very inventive or attractive.

An ultimate trial of TUI is inFORM, a dynamic terrain model by Follmer et al. (2013). It is a 2.5D actuated shape display that supports object tracking, visualization via projection, and both direct and indirect physical manipulation. The shape display, the TerrainTable, is moved by a dense array of pins linked by connecting rods to a larger array of actuators below. Using an array of vertical pins beneath a silicone skin, the table can create virtually any curved surface within an area 52 by 40 inches, 6 inches high. When synchronized with a computer-controlled overhead projector, the TerrainTable makes a convincing topographical map. The table is equipped with an engine connected to a PC, which adjusts the height of the pins according to the raster values to be visualized in 3D on the table. When performing a change of location on the table, such a zoom or pan, pins are sent down, the user chooses the new location with movements of the hands and when the new extent of the raster to be displayed has been evaluated by the underlying GIS engine, the heights of the pins are recalculated according to the new input, and the silicon layer adapts again to produce the new 3D representation on the table. The advantage of the trials is the flexibility of terrain models. Users can manipulate the pins directly and model the terrain of a landscape quickly. However, the equipment is expensive, the system is heavy to move around, and its applicability is limited by the size of pins (Petrasova 2015).

TUI aims to combine the benefits of physical and digital models in the same representation. More generally, TUI gives physical form to digital information, seamlessly coupling the dual worlds of bits and atoms (Ratti et al. 2004b). People can make changes to the interface simply by using their hands. To take advantage of the capabilities, people using the interface must first have the idea that it is useful and that it brings added value. Second, the TUI must be easy to use (Scotta et al. 2006). However, the transportability of the ActiveDesk strategy was not always simple because of the amount, dimensions, and fragility of the components. The table interface, beamer, sensor, screens, and frame to hold components together needed to be moved from one location to another (Scotta et al. 2006).

Instead of the ActiveDesk, concern was also paid to the relationships that occur between different terrains, the physical parameters of terrains, and the landscape processes that occur in these terrains (Mitasova et al. 2006; Ratti et al. 2004a). Illumination of clay and sand was used as a low-cost alternative that also had high performance in terms of communication. Another prototype TUI was developed in 2002 by illuminating clay to model the physical space, using a scanner to capture the model on an ordinary table, and a projector to cast maps of GRASS GIS or a camera to receive infrared light under a transparent table (Piper et al. 2002; US007181362B2 2004) (Ratti et al. 2004a; Ishii et al. 2004). The University of California Davis developed the AR Sandbox to physically create topographic models that can be used as backgrounds for simulations (Kreylos 2020). The sand is overlaid by a digital projection of contour lines and a color elevation map. Data can be sent through a Microsoft Kinect 3D camera into either Ubuntu system or Grass GIS (Petrasova 2015), and into a software program that displays information onto the sand through the projector. Users can manipulate the sand table and observe changes in the elevation map, and the corresponding contour lines are projected back onto the sand. In other words, users shape the real sand which is then augmented in real time with contour lines, elevation color maps, and simulated water flows. By holding the hands under the

Kinect 3D camera, the user can add virtual water to the surface of the sand, flowing over the real surface of the sand with real-time water simulation (Kreylos 2020). The AR Sandbox can be used to teach many geographic concepts to users, such as reading and interpreting contour lines and topographic maps, flooding and formation of watersheds, and can also be used in field trip preparation and trail planning (Kreylos 2020).

TUIs combine the advantages of reality and virtuality by active desk, map projection, and interactive sensing–processing–actuation algorithms. They provide a means of visualization and interaction that attracts participants to the table and invites them to interact with each other, facilitating and assisting the conversation around the table. TUIs make interactions between humans and computers more natural and intuitive by giving digital data a physical form (Petrasova 2015).

Regarding the contents of the tangible table, one effective solution is to couple with GIS (Mitasova et al. 2006). Mitasova et al. have worked steadily with tangible GIS for decades (Maquil et al. 2015; Mitasova et al. 2006 2007). The latest development of TUI is the Tangible Landscape Project using GIS. GIS offers a set of ready-to-use tools for different types of geospatial analyses and simulations as well as an interface for visualization (Petrasova et al. 2014). However, because of the unintuitive nature of understanding and manipulating physical objects in the abstract, systems that work in the digital space via a graphical user interface (GUI) are often so challenging to learn and use that they restrict creativity (Petrasova 2015).

Tangible landscape is a tangible interface for GIS. It interactively couples physical and digital models of a landscape so that users can intuitively explore, model, and analyze geospatial data in a collaborative environment. Conceptually, tangible landscape gives users the feel of GIS in their hands as they can feel the shape of the topography, naturally sculpt new landforms, and interact with simulations like water flow. Since it only affords a bird's-eye view of the landscape, some attempts coupled it with an immersive virtual environment so that users can physically walk around the modeled landscape and visualize it at a human scale (Tabrizian et al. 2016; Harmon et al. 2016; Petrasova et al. 2018). Tangible landscape is a free, open source project with source code hosted on GitHub.

Nowadays, TUIs are increasingly accepted as an alternative paradigm to the more conventional GUIs (Ullmer and Ishii 2000). More than 150 facilities around the world have installed and are using AR Sandbox in various fields, mostly in education (Kreylos 2020). However, despite its popularity, its performance has not been evaluated objectively except in the recent research by Harmon et al. (2018). In their research, landscape architecture students, academics, and professionals were given a series of fundamental landscape design tasks—topographic modeling, cut-and-fill analysis, and water flow modeling. It turned out that the tangible modeling tool helped participants build more accurate models that better represented morphological features than with either digital or analog hand modeling. Participants were able to work in a rapid, iterative process informed by real-time geospatial analytics and simulations. With the aid of real-time simulations, they were able to quickly understand and then manipulate to see how complex topography controls the flow of water.

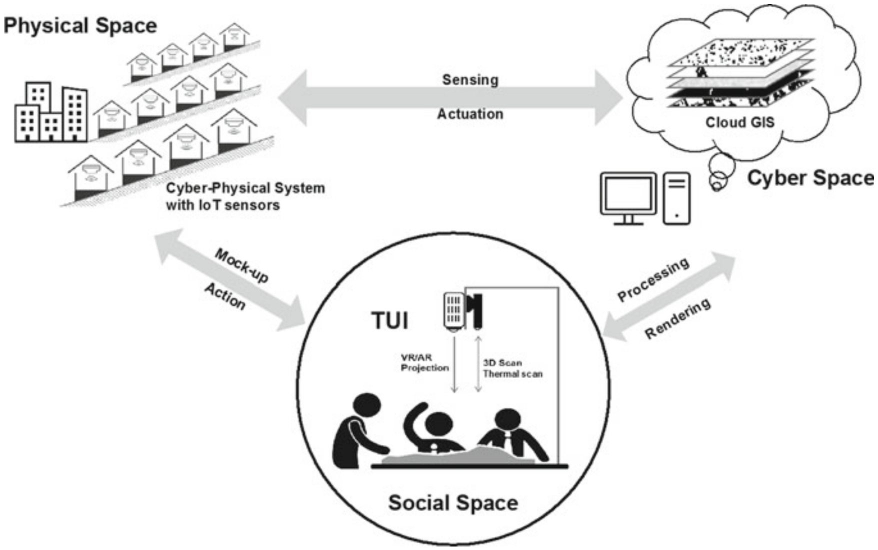


Fig. 2.1 A conceptual extension of TUI for the interaction of physical space, cyber space, and social space

We consider that the tangible user interface could be a bridge to connect physical space of real world, cyber space in computer world and users in social world, as illustrated in Fig. 2.1. The physical space is mocked up to the TUI table and monitored by IoT sensor to clous GIS in cyber spaces. The behaviors of users at the tangible table are scanned by 3D or thermal scanners and processed in GIS. The results shall be rendered and projected back on the tangible deck for user communications and actions to the real world. The detail of this novel idea is going to be discussed in the following sections.

2.3 CPS Platform in the Geographic Dimension

2.3.1 CPS, IoT, and Geo CPS

Yan and Sakairi (2019) have conducted an intensive review on the histories of key geographic technologies and then proposed the term Geo CPS.

CPS, proposed first Branicky et al. (2001), generally refers to physical and engineered systems whose operations are monitored, controlled, coordinated, and integrated by a computing and communicating core (Monostori et al. 2016; Hu et al. 2012; Lee and Seshia 2015; Liu et al. 2017). The functionality of CPS is built on the ability of sensing, cognition, and mapping of the physical space deployed in a geospatial context. “CPS requires the close interaction between the two distinct worlds. The interactions involve the discrete dynamics in the cyber space and the continuous dynamics in the physical space" (Shen 2015). The emergence of IoT has rapidly accelerated the integration of the two worlds, and precision of CPS has significantly improved. The commonality of CPS and IoT is the interaction between the cyber world and physical world.

CPS spatialized in the geographic world is referred to as "Geo CPS" (Yan and Sakairi 2019). Geo CPS is seen as a means of coming to grips with both the static and dynamic spatial relations between and among cyber and physical worlds. The physical world outside the laboratory is much more complex than indoor and comes with a high degree of uncertainty. They are often safety–critical, so the existing techniques focus on reducing latency to provide real-time performance. These open conditions call for advanced specifications in system design, power supply, and protocols for real-time communication. For example, driverless vehicles must simultaneously respond to traffic conditions, and healthcare robots must communicate with patients according to their conditions. The performance of Geo CPS will be determined by the ability of systems to process, analyze, and represent the vast amount of data that are gathered and stored.

Yan and Sakairi (2019) have proposed the basic framework of Geo CPS in which the bold horizontal line expresses the interactions between cyber and physical worlds. Sensing is the technology to recognize the static and dynamic situation of the physical world, cognition is applied to understand the ways in which the "world" works, and mapping is for rebuilding the physical "world" in cyber space. However, the interface between the cyber and physical worlds was not defined, the structure and function of the interface were not developed yet.

2.3.2 Geo CPS Platform

A key feature of Geo CPS is the integration of information within each space and the interaction between the pairs of spaces. Information integration within cyber space and physical space is characterized as Pseudo CPS and True-CPS, respectively (Yan and Sakairi 2019).

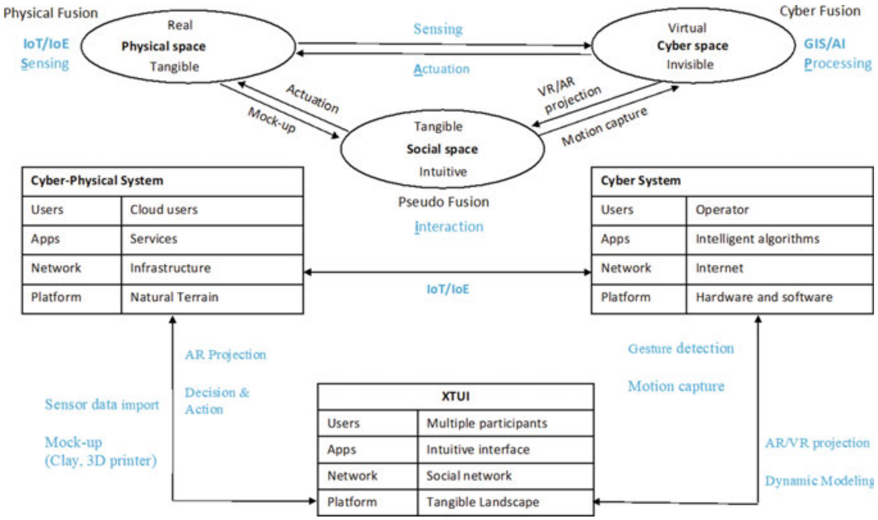
Pseudo CPS achieves information integration by using the position of IoT as a key to overlay real-time observations onto cyber space. This kind of pseudo CPS has been widely realized and applied. Doctors can provide telemedicine while they observe a monitor. Space centers can control a space station while watching monitors. Disaster response headquarters can make emergency response decisions while observing a large screen that combines information from multiple locations and departmental functions. Traffic management centers can monitor road conditions in real time. Conventional car navigation was also basically such an example. The GNSS system obtains the location, which is displayed on a digital map provided by DVD or internal HDD, and the user sees the current location. Road traffic information is sent with a delay of a few minutes via vehicle information and communication system (for instance, VICS in Japan) and that is displayed on the monitor. The information is in a separate layer, not incorporated into the map data. A similar technique is augmented reality (AR) (Khalid et al. 2015). GIS and computer-assisted design (CAD) are the same. Objects and systems in cyber space are not tactile and are too complex for non-professionals to understand. The dysconnectivity of closed systems with each other makes the feedback of information from cyber space to physical space difficult in real time. An operator plays a key role in the effectiveness of the system. There are other issues as well. For example, operator training takes time, systems may not be well suited to strategic decision-making, and systems might be partially optimized but not necessarily result in improved overall productivity.

On the other hand, a true CPS (TCPS) is a system that combines information from and to the physical world tightly in order to actuate objects. Sensors interact with object cross layers. Driverless vehicles are an example in the geographic dimension, using IoT online to obtain and monitor vehicle position, traffic conditions, and the peripheral environment in the physical world, process everything in real time, conduct integrated analysis for any layer, and actuate people and moving objects. Here, location-aware IoT in situ is the key to make the interaction possible. A TCPS places an emphasis on interactive functionality of systems. Sensing, processing, and actuation are installed, invisible, and work without human intervention. For a mature, complete system, this works well. However, problem-solving and system development often require intensive communications between developers and users. Solutions for social and environmental problems culminate from the participation of stakeholders. The interface between the cyber and physical worlds is critical in the installation of technologies.

As a solution to maximize the advantages and compensate for the disadvantages of PCPS and TCPS, we propose the Geo CPS platform with XTUI to accelerate the communication across spaces in specific social–physical contexts. The goal of the platform is to provide an intuitive tool for developers and stakeholders to understand how the physical environment evolves and how the interactions could be improved with cyber technologies. As functions, the tools actuate sensors in the physical space in real time and processors in cyber space and motivate people intuitively in the social space in order to co-design solutions to solve complex problems. As shown in Fig. 2.2, XTUI links physical, cyber, and social spaces with a common system architecture consisting of platform, network, apps, and users. The details of the concept and system architecture are discussed in the next section.

2.4 eXtended TUI for the Geo CPS Platform

The philosophy behind TUIs is to allow people to interact with computers via familiar tangible objects, therefore taking advantage of the richness of the tactile world combined with the power of numerical simulations (Ratti et al. 2004a). Informational flow in TUIs, from the acquisition of user input and the generation of GIS processing, to map projection and manipulation of the mock-up, forms a pseudo cycle of sensing,



Cyber-Physical System	
Users	Cloud users
Apps	Services
Network	Infrastructure
Platform	Natural Terrain

Cyber System	
Users	Operator
Apps	Intelligent algorithms
Network	Internet
Platform	Hardware and software

XTUI	
Users	Multiple participants
Apps	Intuitive interface
Network	Social network
Platform	Tangible Landscape

Fig. 2.2 The framework of XTUI and its system architecture, iSPA

processing and actuation in the laboratory. Our purpose is to create a TUI applicable for the development of CPS solutions in geographic and participatory conditions.

2.4.1 Conceptual Framework of eXtended TUI

The conceptual framework of eXtended Tangible User Interface (XTUI) is illustrated in Fig. 2.2. It is composed of physical, cyber, and social spaces, plus the interactions between each pair. Each space possesses its own structure of layers (platform, network, services, and users). XTUI is vital in the triangular relationships, which completes the link from the tangible table with the physical environment and cyber space. While maintaining interactivity for visualization, XTUI extends the functions in three ways.

First, XTUI considers TUI not only as an interface but also as a platform for participatory design of system solutions on social issues. TUI has indeed been a tool for human communications because from the beginning it has aimed to bridge gaps between cyber space and the physical environment, as well as the foreground and background of human activities (Ishii and Ullmer 1997). Compared with the cyber and physical spaces, however, the concept of TUI was generally limited to technical operation while other important factors (the social context and community of users) were hidden. Human factors did not receive much attention in applications so far. In XTUI, we introduce the user community (here referred to as the social space). Thus, the mission of XTUI is extended to the co-design of solutions for problem-solving, rather than mainly the demonstration of a pre-designed product.

This provides an innovative perspective for developing applications of TUI in disaster risk management.

Second, XTUI extends the target of TUI from the tangible desk to the real world through the IoT network and human network. Programs and algorithms can be tested by TUI with stakeholders so TUI is used as a participatory testbed. Human communication and decisions can be tested on the tangible table, reflected in cyber space, and actuated remotely with sensors and rovers. This extension connects the TUI tightly to the physical world while the mock-up becomes a living simulator in a specific context.

Third, XTUI is not only a visualization tool but also a platform for community and stakeholders to co-design solutions with a participatory approach, and it is used as a testbed in a living laboratory, rather than a manufacturing laboratory. XTUI establishes a third apex to cyber and physical systems by adding the interactive and intuitive human factor of social space, so that the system architecture of CPS becomes an *interaction of sensing, processing and actuation.* We call this structure *iSPA*, the featured system architecture of XTUI. This feature particularly suits to disaster risk communication in situ with support of scientific data.

In fact, CPS, GIS, and XTUI represent three ways of understanding, processing, and manipulating our world, in which each technology takes a unique position. CPS emphasizes direct interactions with the physical world; GIS manipulates those objects in the cyber world; XTUI fills the gap by brings the physical and virtual objects together into the social space for decision-making.

2.4.2 System Architecture of XTUI

Information integration in cyber–physical–social worlds has been studied substantially. As illustrated in Fig. 2.2, a computational cyber space is generally composed of hardware, operating system, applications, and users/clients. A physical space is constructed on physical terrain, social infrastructure including road and communication networks, institutions, and user services. The system architecture of CPS is often discussed with four layers: sensor/actuator, supervisory, control, and applications. The sensor/actuator layer contains various devices in the physical world. The latest TUIs use GIS, CAD, VR, and AR as applications to render geospatial content for map projections (Maquil et al. 2015, 2018). However, the interaction between all three spaces has not been discussed as much as bilateral mutual interactions between cyber, physical, and social spaces.

The key concept of the system architecture for XTUI is conceptually structured as iSPA, as shown in Fig. 2.2, where S expresses the part of sensing of cyber–physical system, P expresses algorithms of processing in cyber system, i expresses interaction of users with cyber and physical systems, and A expresses direct or indirect actuations between the cyber-physical systems through social systems.

We see that three spaces are considered similarly in the bottom-up operational structure by the layers of platform, network, apps, and users. A physical system works on physical terrain, infrastructure, private and public services, and cloud of users for data fusion while a cyber system is on computer hardware and software, the Internet, intelligent algorithms, and operators for virtual data fusion. XTUI is operated on tangible landscape, with a social network, intuitive interface, and multiple participants. While CPS is often considered to be interactive between cyber and physical systems only, the system built on iSPA is inclusive, including not only invisible communications in cyber–physical systems but also decisions and actions of the participation and discussion in the social space. The role of XTUI is to activate communication intuitively.

With iSPA, information is aggregated locally and delivered to the Internet in real time. The supervisory layer organizes data sources, conducts analysis and simulations, and provides the results to the application layer. IoT devices are monitored and controlled at the control layer. Eventually, we expect value to be created from connectivity based on a platform by integrated utilization of sensor data from different industries and sectors, as well as public data, and citizen data.

Therefore, iSPA provides a system structure to co-design the solutions of problems in the physical world, in a participatory fashion. Those solutions will be developed through communications with XTUI in a series of practices. By using iSPA, the functions and interactions between cyber, physical, and social spaces can be simulated at the community level. The performance of such systems will depend on the depth and breadth of interactions, as described in Fig. 2.1. A shallow level of interactions relays only data and messages. A deep loop will learn the causes and effects inside virtual content with real-time observation in the physical space and human operation in the social space. The experience of learning may start from the mock-up stage of XTUI, but more attention should be extended to multi-scales of cause and effect in the physical world.

2.4.3 Functions of Geo CPS Platform

Figure 2.3 presents the system functions of the Geo CPS platform. It is roughly categorized (on the left) in terms of iSPA, with *sensing* and *actuation* at the lower level and *processing* and *interaction* at the higher level. The column highlighted in gray expresses the classes of functions where sensor and actuation devices are grouped with network and communication protocol. Functions relevant to cyber space (data management, mining, and machine learning, etc.), are located near GIS, VR/AR, and map projection. XTUI brings various user services to the platform in tangible ways by using 2.5D, 3D mock-up, or illuminating clay in the physical world. Tangible landscape objects are enhanced with GIS projection or AR/VR simulation. Tangible objects could be a mock-up of buildings, facilities, or any other objects. Multiple users can touch the 2.5D or 3D objects to retrieve the deep layer of cyber spaces by using app interfaces like REST and SPARQL as well as any customized API. The potential of XTUI and the platform is demonstrated through a series of working scenarios.

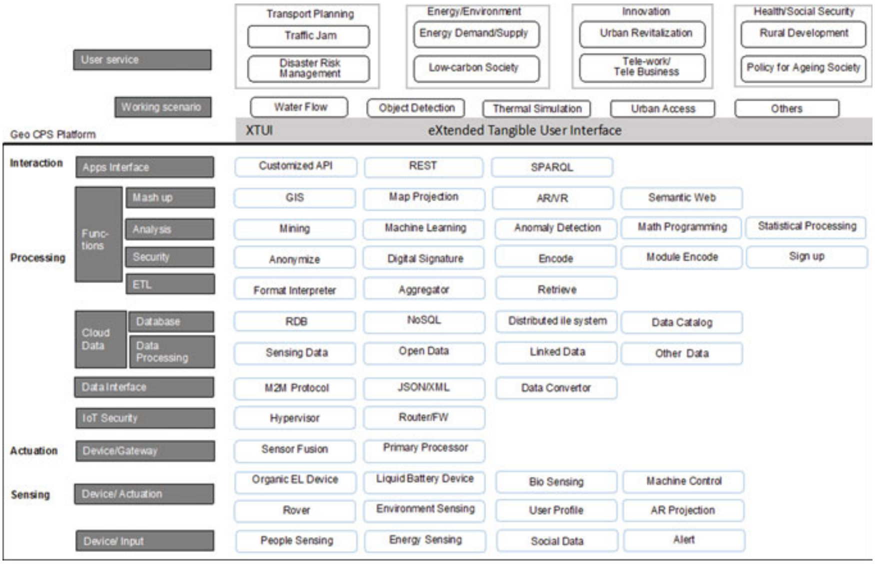


Fig. 2.3 System functions of Geo CPS Platform with XTUI

User services could be diverse, ranging from transportation planning, energy and environmental management, to innovation, social revitalization, and human health and security. Issues in each sector could be described as applied cases in the physical world by the integration of information from inside and interactions with the outside. Working scenarios, such as water flow, object detection, thermal simulation, and urban access assessment, provide several fundamental tools for the development of solutions. Meanwhile, ideas, feasibility, and applicability can be examined in a Geo CPS platform with XTUI.

2.4.4 *Working Scenarios*

The development of TUI has evolved since the early 1990s from (1) hand gestures and grasping to (2) interactive simulations of physical worlds, (3) working scenarios, and (4) commercial applications (Fitzmaurice et al. 1995). Although the tools have evolved from graspable bits and dynamic terrain models to AR Sandbox and Tangible Landscape, the fundamental issues have not changed significantly. To use TUIs, people need to realize that they can be useful and bring added value (Scotta et al. 2006). Systems that model elevation, contours, and water flow on an abstract landscape are limited in the scope of potential applications (Petrasova 2015), but the potential of the sandbox can be expanded by improving interactions in cyber space. Thus, our idea was to extend TUI with CPS and expand scenarios that link directly with the physical world.

To address the relative absence of TUI in urban-related applications, we proposed scenarios for a Geo CPS platform with XTUI using thermal cameras to simulate the thermal radiation of different building materials. The landscape model is made by contour map and buildings created by 3D printer. A thermal camera is installed to monitor radiation in the physical model. Solar radiation from materials with different albedo demonstrates the effects of anthropogenic surfaces on the living environment. By manipulating the material of the ground surface and building surfaces, the system simulates changes in real time and projects the results back onto the tangible table. Meanwhile, the system dynamically connects thermal sensors in situ to the tangible table and demonstrates the temporal change of observations. With this, environmental temperature can be simultaneously brought into discussion. By comparing reality and simulation in cyber–physical spaces, users in the social space are able to easily understand the effects of reactions. This can be very useful for discussions on mitigation of the urban heat island effect, for example.

Another scenario of XTUI is the accessibility to urban facilities. Urban access is largely influenced by topography and walkability. Many neighborhoods of cities in the world are built on hilly topographies, which results in extra effort required by people who are walking, and the extra burden could be more severe for the elderly and disabled persons. Having ways to assess walkability and visualize accessibility in different landscapes for people with different health conditions will help residents better understand the built environment and will assist urban planners and developers to better locate urban facilities. An algorithm using GIS was developed in Nakayama and Yan (2019) to evaluate "shop sheds." This algorithm was installed in an XTUI platform with topography mocked-up by contour map and buildings created by 3D printer in 2.5D. The "walkable shed" from a grocery shop or convenience store is then evaluated and projected onto the 3D model. Users can relocate a target object on the tangible environment and then update the accessibility via the shortest road network and consideration of "walk load" by age cohort. When the algorithm interacts with in situ weather conditions, the walkable paths and consumption of energy can be calibrated in real time.

The third scenario is application for risk communication in disaster management. Disaster management is one of the most targeted uses of TUIs. A popular working scenario in TUIs is for flood simulation in tangible landscape. While multiple users modify the landscape with sand, the elevation is scanned with an infrared camera and modeled in GIS. The contour map is generated and again projected on the TUI. Rainfall runoff, the effects of a reservoir, and the collapse of a dam can be simulated in real time. These intuitive education tools can help users understand the mechanisms of hydrology. Environmental and river sensors in the physical world bring information of water level to the social spaces and provide observations in real time for simulators in virtual space. Tangible landscape and projection of flooding simulators in XTUI give intuitive presentation of water level, flooding risk, and even evacuation routes. It can also easily simulate the impacts of collapses of dams and river banks and present the results on the tangible landscape.

2.5 Experiment and Potential of Geo CPS

2.5.1 Community Trial in Urban Living Lab

Map projection is often used in participatory urban planning and design. Those cases often consider TUI as a tool for visualization of cyber content only, without tight connections with the physical and social contexts at the local level. For instance, Maquil et al. (2015) introduce the concept of Geospatial Tangible User Interfaces (GTUI) and report on the design and implementation of such a GTUI to support stakeholder participation in collaborative urban planning. The proposed system uses physical objects to interact with large digital maps and geospatial data projected onto a tabletop. However, no researchers have mentioned how to set up the user community in a social context.

We brought the Geo CPS with XTUI to an Urban Living Lab for a community trial. An Urban Living Lab (ULL) is a geographical or institutional location or approach to have researchers, citizens, companies, and governments voluntarily cooperate in experimentation (McCormick and Hartmann 2017). A ULL provides a platform for governments, businesses, research institutions, communities, and citizens to plan, design, and test products and solutions cooperatively (Thinyane et al. 2012). The intrinsic properties of ULL are to learn from the real world, create knowledge in the real world, and produce solutions that can be applied in real life. Usually, companies and universities bring projects forward, conduct planning, design, application, and testing through co-creation, and receive social feedback. Early on, companies envisioned ULLs as having the purpose of developing, designing, and testing products from the user perspective (Kimbell 2011). This explains how in many cases ULLs were created and used as venues for co-creation or testbeds for product development by companies.

Yokohama has developed as a port town, with its city center near the waterfront playing a major role as a center of commerce in the Tokyo metropolitan region. Parts of Yokohama facing the mountains have large residential areas that serve as bedroom communities for Tokyo. Many of these residential areas were planned and constructed during Japan's postwar period of high economic growth, so their populations and infrastructure are aging, and the infrastructure is entering a period requiring renewal. To examine this situation, the Yokohama municipal government and Tokyu Corporation (a major private railway company) kicked off a joint project in April 2012 on the "Next-Generation Suburban Town Project" (NST, https://jisedaikogai.jp). Over the years, many study meetings and participatory workshops were organized with residents, resulting in an activity report entitled "2013 Basic Concept for NST: Community Development Vision for the Model District along the Tokyu Den-en-Toshi Line." Following the recommendations presented in the report, Tokyu Corporation established the WISE Living Lab (WLL) in 2017 and opened a facility at the property it owned in Tama-Plaza. WLL is an activity center for NST and has become a forum for residents, governments, businesses, and universities

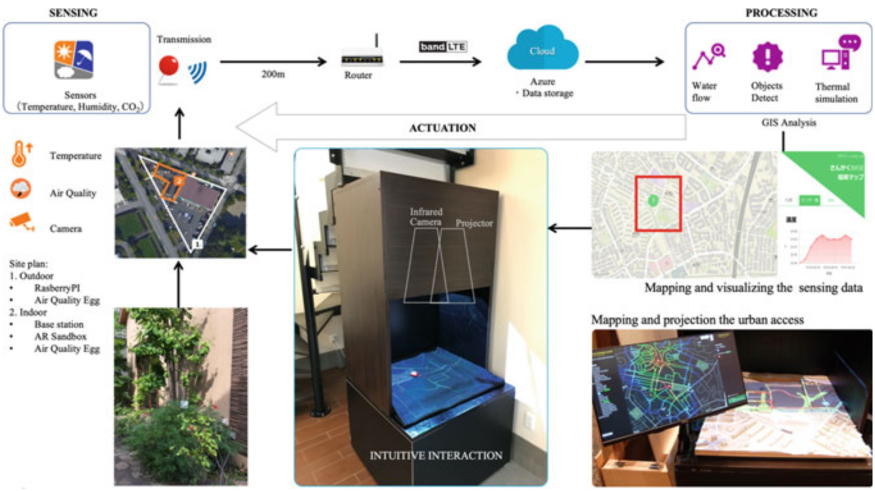


Fig. 2.4 System configuration of XTUI at WISE Living Lab

to communicate about local issues, think together about how to address them, co-create, and produce results. Under this scheme, we launched a project to cooperate with stakeholders, aiming to redesign the food life of the suburban town. A prototype of Geo CPS is installed at WLL. The site condition and system composition are shown in Fig. 2.4.

XTUI in this case is composed of a PC, a projector, an infrared camera to detect gestures and the designed frame. Sensors of temperature and air quality are installed at the living lab indoors and outdoors, and sensing data are transmitted to cloud data storage on the Internet. The data are processed in GIS for mapping and visualization. The processed data are presented by chart or map on the project website in virtual space. Meanwhile, the maps are projected onto a 3D model of the area. As a result, environmental conditions can be monitored in situ and the results can be reflected in the XTUI in real time. Participants can manipulate the land surface mocked up by clay or sand, or street blocks, buildings or road pavement by 3D printed objects. The participants' operations are captured by infrared camera and projected back as the thermal effect of modifications.

The walking accessibility of the area is calculated and displayed by monitor in a cyber system. It is projected onto the 3D model with the color red representing high accessibility along the road network. The user can move a tangible icon of a facility on the table to re-locate it. This interaction is in real time, so the result can be confirmed immediately. Overall, this XTUI helps users better understand their living conditions and consider ways to improve them.

2.5.2 Potential for Disaster Risk Reduction (DRR)

Disaster risk is the intersection of events, exposure, and vulnerability (IPCC 2012). Reducing the risk requires innovative techniques that can detect natural abnormalities quickly, alert early, and improve public awareness effectively. Geotechnology has attracted high expectations and found many applications due to its advanced use of technologies and potential for public participation.

For decades, many have advocated for public participation in disaster risk management, but in reality, it remains elusive (Ray et al. 2017). Samaddar et al. (2017) examined the process and identified outcome-based factors that account for successful participatory disaster risk management. The results unveiled that planners and practitioners are still struggling to find ways to meaningfully involve local communities in disaster management programs; so far, apparently successful projects and initiatives have seldom been scaled up or replicated. The reason for this is that no comprehensive framework for participatory disaster risk management exists, and no systematic evaluation has been made to assess the necessary elements and appropriate paths for meaningful public participation (Samaddar et al. 2017).

Some tools incorporate GIS and GPS and can be used by trained local communities to assess flood risk intensity at a local level and hence develop risk management plans (Singh 2014). Participatory GIS (PGIS) offers tools that can be used to help the public be meaningfully involved in decision-making processes affecting their communities (Jankowski 2009). PGIS usually involves communities in the production of spatial data and spatial decision-making (White and Ross 1984). Technologies utilized in PGIS have involved both commercially available and open-source GIS software, and more recently, free software. However, which PGIS tools should be used in a given participatory process depends largely on what level of participation is to be achieved (Jankowski 2009). Hazard inventories can also be produced using participatory mapping and PGIS. WebGIS was often used to enhance community resilience to flooding by identifying the Tangible and Intangible Local Flood Culture of the City of York (Chitty and Sprega 2017).

Cadag and Gaillard (2012) developed participatory three-dimensional modeling or mapping (P3DM) in the Philippines by building stand-alone scaled relief maps made of locally available materials (e.g., cardboard, paper) and thematic layers of geographical information. Guerin and Carrera (2010) used an interactive tangible 3D platform for the modeling and management of wildfires, with an interactive tangible 3D platform applied to conduct wildfire training, incident command and community outreach activities by allowing users to interactively visualize a variety of scenarios on sand tables, based on underlying wildfire, traffic, smoke, rain, and incident command models. "SandBox-FM" is a tool developed by Ottevanger et al. to combine either a Delft3D-Flexible Mesh (FM) or an XBeach model with Tangible Landscape (Ottevanger et al. 2017). Tonini et al. (2017) applied tangible landscape to the complex problem of managing an emerging infectious disease affecting trees in California, sudden oak death, and explored its potential to generate co-learning and collaborative management strategies among actors representing stakeholders with competing management aims.

IoT technology has also attracted interest for DRR (Park et al. 2018). A framework for how systems will come together for the purposes of DRR was proposed by (Baloyi and Telukdarie 2018; Ray et al. 2017). For instance, Baloyi and Telukdarie (2018) proposed a multi-layer structure of a cyber–physical system, but it lacks explicit consideration of the human interface. Zhang et al. (2018) reviewed advanced sensing, processing, and data fusion technology and described a framework for building an IoT-based geospatial sensor web focusing on service web capacity with four key methods, namely, integrated management, collaborative observation, scalable processing, and fusion. Some studies have also reviewed prototypes and applications for environmental, hydrological, and natural disaster analysis. Unfortunately, they mostly focus on sensing technology and pay less attention to integration and interaction with cyber and social factors, while interactions with user communities are generally outside their scope.

Geo CPS has significant potential for applications in disaster management at the community level by enhancing the integration and interaction of cyber–physical–social spaces. Figure 2.5 shows scenes in the community trial at WLL mentioned above, where GIS content is projected on the Tangible Table. In the photo on the left, the colored road network represents accessibility to a re-located convenience store, and the green coverage represents the landform of the neighborhood and low-lying areas prone to flooding. AR GIS and the Tangible Table bring together information in GIS and cyber space intuitively and interactively with participants.

Fig. 2.5 Geo CPS experiment in the suburbs of Yokohama City. **a** Tangible Table with topographic information before development, accessibility after development. **b** Public participation with AR of map projection on XTUI

2.6 Conclusions

This chapter focused on the integration of geotechnology with IoT and TUI and presented an innovative picture of a Geo CPS platform with eXtended TUI (XTUI) for intuitive interaction in the cyber, physical, and social spaces.

Elemental technologies such as GIS, AR/VR, and GNSS have developed significantly and come into popular use in the mainstream of information society. Emerging technologies such as IoT and CPS are driving a new wave of industrial innovation, as in the example of Society 5.0. However, applications so far remain mostly in scientific and manufacturing laboratories and have not so easily found a place in light of the urgent demands of society. Geo CPS as a platform aims to bridge gaps that exist between cutting edge technologies, established geospatial industries, and practical issues of society. The platform, composed of CPS, GIS, and XTUI, takes the common advantages of the elemental technologies in the geospatial dimension and provides a new perspective to develop CPS solutions by focusing on integration and interaction in the physical, cyber, and social spaces. The platform requires developers to understand the location-specific context and pay attention to interactive processes with stakeholders and the synergistic effects of communications. The introduction of Geo CPS at the Urban Living Lab exemplified a model of implementation with community, which brings the physical environment visibly onto the XTUI table and intuitively drives interactive discussions. Interactions at the Living Lab create opportunities for system developers and community leaders to co-discover problems, co-design solutions, and co-deliver benefits to society.

Disaster management is mostly a social issue rather technological. Reducing disaster risks and improving resilience of communities require support of information and technology in a way of more real timely with finer datasets and seamless communications. The mission itself is completely location and context sensitive. The Geo CPS platform in this sense considers the importance of physical, cyber, and social spaces simultaneously with a system structure and functions in common structure. The working scenarios demonstrated the feasibility of implementation in community, such as the urban living labs.

The platform presented here is still in its infancy. Its functions have not been fully developed, the sensor network is still in the process of being installed, and scenarios need to be further developed. Nevertheless, we believe there is potential for the innovative ideas introduced here to make significant contributions in many geospatial applications, including disaster risk management.

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