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Development of a 3D Online System for Comparative Study of Architectural Elements in Thai Stupas

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ABSTRACT

Understanding architectural names and semantics is essential for studying historical sites. New educational media in 3D and 2D formats, available online and offline, supports this by using specific buildings to illustrate shapes, positions, and proportions along with names and semantics. This approach works well for initial education, but in-depth study requires comparing architectural elements to identify similarities and differences. Today, comparative learning is recognized as an effective method for enhancing understanding. Therefore, this research focuses on developing a 3D online system for studying the names and semantics of architectural elements in Thai stupas and their architectural elements. The system features a multi-dimensional database and a real-time interactive online interface. It includes the ability to simultaneously view and compare up to three stupa models, enhancing comparative analysis and facilitating a comprehensive understanding of architectural variations. The system is tested using stupas from the Sukhothai, Si Satchanalai, and Kamphaeng Phet Historical Parks to help users appreciate Thai historical sites better. The developed system has been evaluated through teaching experiments, revealing that comparative learning deepens students' understanding. They can predict the names of stupa components, even if they have never seen that particular stupa before, by using the similarities or differences in elements as preliminary information to guess the semantics. Students who participated in the comparative interface were also able to improve their knowledge retention compared to learning with a single 3D interface.

Keywords: semantic annotation, virtual heritage, web-based 3d visualization, comparative learning, architectural elements, Thai stupas architecture

INTRODUCTION

One essential process in studying historical sites is understanding the names and meanings of architectural elements, as these form the foundation of heritage education. However, traditional 2D media often limit the depth of comparative study, as they lack the interactive functionality needed for effective analysis of shapes, proportions, and spatial relationships among elements. Although textual information can explain the names or semantics of these elements, its unidirectional format is often only effective for introductory learning. As learners advance, it becomes crucial to compare architectural components to reveal similarities and differences among closely related sites. Recent educational research widely acknowledges that comparative methods improve learning efficiency and deepen understanding (Goldstone et al., 2010; Rittle-Johnson & Star, 2011).

Recent advances in 3D visualization technology on online platforms offer a promising solution, providing opportunities for users to explore historical sites in real-time, interactive formats. Such 3D models simplify architectural explanations, making them accessible even to those without architectural drawing skills. However, existing resources still lack a system specifically designed for simultaneous viewing and in-depth comparison of multiple 3D models. Addressing this gap, this research presents a novel online system called STUPA (Semantic annotated Three-dimensional system for Understanding Preserved Architectures) that enables users to view and compare multiple 3D models of architectural elements simultaneously, offering a uniquely interactive approach to studying historical sites and architectural semantics. Users of this system can view and compare up to three stupas simultaneously, with access to both 3D and 2D information. The 3D models in this system are generated through photogrammetry from photographic data of real-world architecture, as well as interactively created 3D models based on the collected data.

Objective

This research aims to develop an online information system for studying the names and semantics of architectural elements of historical sites, utilizing 3D models as a medium. Users of this system can compare architectural elements from various sites, leading to a deeper understanding of architecture.

The interface of our developed system can support the presentation of 3D models in either one, two, or three stupas simultaneously. The initial database of this system utilizes 27 stupas within the Sukhothai, Sri Satchanalai, Kamphaeng Phet Historical Park as testing areas. The content of this research is divided into two main parts: (1) The process of collecting, managing, and creating data for presentation in the system, including both 3D and 2D data, as well as the semantic annotation transfer process; and (2) The development of an information system capable of presenting semantic relationships between elements from various stupas.

Comparative study of the names and meanings of architectural elements through our developed system helps learners gain deeper insights than studying buildings in isolation. Here are the advantages:

1. Observation of Similarities and Differences: By comparing architectural elements across multiple buildings, learners can identify unique features and commonalities, which deepen their understanding of design concepts, architectural styles, and the reasons why designers incorporated certain elements in specific contexts.
2. Understanding Systematic Ideas and Specialized Terminology in Architecture: Comparative study allows learners to observe recurring structures and terminology used across different buildings. This helps them understand the links between specific terms and design choices across eras, regions, and stylistic traditions. For example, seeing similar elements referred to differently reveals cultural perspectives and terminological diversity.

3. Insight into Historical Development: Comparison helps learners grasp the broader evolution of architectural forms over time or in various regions, shedding light on the influences of technology, materials, and beliefs across different architectural periods.

LITERATURE REVIEW

This research aims to adapt the study by comparing and analyzing the architectural element's semantics on 3D models. Currently, it is widely recognized that comparative learning is an effective process and has been applied in various fields of study (Goldstone, et al., 2010; Rittle-Johnson & Star, 2011). This process can assist learning across diverse subjects, from preschool children (Namy & Gentner, 2002) to elementary school students (Star & Rittle-Johnson, 2009), up to undergraduate students (Gentner et al., 2003). This form of learning involves comparing or identifying differences between concepts, ideas, or subjects to enhance learners' deep comprehension (Hattikudur & Alibali, 2010). Even in the fields of architecture and cultural heritage, the comparative study process has already been tested, both in classroom trials (with evaluation results showing the significant potential of this method) (Seeumpornroj, 2021) and in research for comparing stupa elements (Aung, 2022).

Employing this method promotes critical thinking, problem-solving abilities and enhances long-term retention, which differs from traditional learning methods that often rely on rote memorization.

Today, there are many research studies related to the semantic annotation of cultural heritage data. These encompass both 3D models and 2D media, providing semantics to certain parts as well as the entirety of a model. Approaches to semantic annotation in three-dimensional models have been explored in various studies, such as those dealing with 3D semantics of artifacts, like the work of Yu et al. (2013). This process requires 3D segmentation and establishing relationships between three-dimensional elements and semantic data. The semantic enriched three-dimensional data can be derived from reality-based raw data acquired through laser scanning or photogrammetry (Chiabrando et al., 2019; Garozzo et al., 2017), as well as conceptual models created from manual modeling. The purpose of creating such models is to represent architectural forms in an ideal state, not necessarily adhering strictly to real-world conditions. These models are created with completeness in mind and do not emphasize decay, degradation, or distortion. Upon observing this type of model, viewers can more easily comprehend architectural shapes and forms. The current trend in employing these models involves the utilization of Heritage Building Information Modelling (HBIM) (Bacci et al., 2019; Bruno & Roncella, 2019; Lo Turco et al., 2017; Previtali et al., 2020; Simeone et al., 2019).

Semantic annotation for cultural heritage can be applied to both two-dimensional media and three-dimensional models, providing semantics to certain parts as well as the entirety of a model. Approaches to semantic annotation in three-dimensional models have been explored in various studies, such as those dealing with 3D semantics of artifacts, like the work of Yu et al. (2013). This process requires 3D segmentation and establishing relationships between three-dimensional elements and semantic data. The semantic enriched three-dimensional data can be derived from reality-based raw data acquired through laser scanning or photogrammetry (Chiabrando et al., 2019; Garozzo et al., 2017), as well as conceptual models created from manual modeling. The purpose of creating such models is to represent architectural forms in an ideal state. These models are geometrically reconstructed shapes in three dimensions with completeness in mind. Upon observing this type of model, viewers can more easily comprehend architectural shapes and forms. The working process in this phase can be categorized into three approaches: (1) Automatically Defining Components and Creating Semantic Descriptions: This approach often employs AI methods like Machine Learning (ML) or Deep Learning (DL) to automate the process (Matrone, et al., 2020; Pierdicca et al., 2020). (2) Semi-Automatic Approach: A hybrid automated approach that combines manual intervention with automation (Croce et al., 2020). (3) Manual Approach: A fully manual approach where human expertise plays a significant role (Apollonio et al., 2013; Artopoulos et al., 2023; Costamagna & Spanò, 2012; De Luca et al., 2011). However, the data that has been annotated will be tied to one selected representation. If we wish to switch or display various representations simultaneously, the annotated data will not appear or be unrelated to the chosen representation. To have semantic relations consistently across different data types, we need to rely on the semantic annotation transfer process. This process can occur during the architectural heritage study in various cases, such as transferring semantics from a 3D model to 2D images (Busayarat et al., 2010), from a 2D image to a 3D model (Messaoudi et al., 2018), from a 2D image to a 3D model and then distributing to other spatially referenced 2D images (Manuel et al., 2016), or transferring between different three-dimensional models themselves, such as transferring from a lower resolution mesh to a higher resolution one (Scalas et al., 2017). This concept can also be used in the process of finding similar styles in building models (Lun et al., 2015).

Once both 2D and 3D data have been semantically annotated, we need to study methods for presenting this semantically enriched model through online media. Many research projects have developed online systems that support input, search, and display of semantic information in 2D media, such as the study by Schreiber et al. (2008). Simultaneously, presenting semantic information on 3D models comes in various forms. For instance, research by Apollonio et al. (2018) has developed an information system that supports semantic annotation on three-dimensional models and displays data on an online interface. The NUBES online system (Stefani et al., 2013) is capable of presenting semantically linked data with heterogeneous representations. Additionally, the Aïoli system (Abergel et al., 2023; Roussel & De Luca, 2023) is a cloud platform that facilitates the transfer of semantics information between 2D images and 3D models. The advantages, disadvantages, and research gaps of the mentioned research projects can be compared in the following table (Table 1).

Table 1

A Comparative Table of Research Related to the Presentation of Three-Dimensional Models Enriched With Semantic Information Through Online Media

Research Project	Research Project	Research Project	Research Project
Schreiber et al. (2008)	- Open-source software for semantic annotation and search.	- Limited to keyword-based queries; lacks advanced querying functionalities.	- Does not address integration of 3D models with semantic information for more immersive learning experiences.
	- Supports semantic grouping of search results, enhancing discoverability.	- Primarily focused on 2D media; lacks interactive visualization options for deeper engagement.	
Apollonio et al. (2018)	- Provides an interactive web-based information system for restoration projects.	- Complexity in data management; potential difficulty in standardizing restoration data.	- Limited scalability and adaptability to various types of restoration projects beyond the specific study area.
	- Integrates highly detailed 3D visualizations with data mapping on surfaces.	- May require extensive training for users to fully utilize all functionalities effectively.	

Table 1 (Continued)

Research Project	Research Project	Research Project	Research Project
NUBES online system (Stefani et al., 2013)	- Interactive platform enabling semantic annotation of cultural monuments.	- Manual alignment of images may be time-consuming for users; reliance on user input may lead to errors.	- Does not allow simultaneous comparison of multiple models or data types for deeper analysis.
	- Facilitates interaction between users and both 2D images and 3D models, enhancing engagement.	- Limited focus on how these interactions can be utilized in educational contexts for different audiences.	
Aïoli platform (Abergel et al., 2023)	- Integrates multi-dimensional and multi-format data into a cohesive cloud-based system.	- Complexity in managing diverse data formats may hinder usability for non-technical users.	- Lack of specific focus on the effectiveness of the platform in educational settings or comparative studies.
	- Provides a collaborative environment for documenting and enriching cultural heritage data.	- Potential challenges in standardizing input from various disciplines due to differing methodologies	

Background

Studies and Selection of Sites

Stupas are architectural structures in Buddhism that originated in India. In Thailand, various Buddhist stupas have appeared as archaeological evidence since the Dvaravati period, around the 10th to 11th centuries. They were influenced by the artistic style of Gupta art in India. Subsequently, they underwent further development, influenced by the centers of Buddhism in later periods such as those in Sri Lanka and Pagan. They have also been adapted to local preferences and societal developments. Thai people refer to a stupa as "Chedi," derived from the term "Cetya" in Pali or "Caitiya" in Sanskrit, which carries the meaning of "reminiscence or something that brings to mind." This meaning is broader than that of "Stupa." On the other hand, the term "stupa" is in Sanskrit and has the same meaning as "Thopa" in Pali, referring to a semi-circular burial mound. In Thailand, the term "Stupa" is often used interchangeably with “Chedi” to imply the same meaning. In the regions of Sukhothai, Sri Satchanalai, and Kamphaeng Phet, there are three forms of stupa, namely the “Rakang” (bell-shaped stupa), the “Phumkhaobin” (lotus bud-shaped stupa), and the “Prasat” (castle-shaped stupa).

We established criteria for selecting stupas, which must be stupas from significant temples located within the historical park area and in complete condition. This was done to allow users to observe the elements of the stupas comprehensively and understand the interrelation between each part. A total of 27 stupas were selected, categorized as follows: 12 stupas from the Sukhothai Historical Park, nine stupas from the Sri Satchanalai Historical Park, and six stupas from the Kamphaeng Phet Historical Park.

Studies of Architectural Element Terminology

The objective of this research is to develop media that allows users to compare the elements of stupas. Therefore, it is necessary to address issues such as identical names, semantics, or forms of elements, as well as the challenge of linking these attributes (name-semantic-form) to each stupa element. These issues can occur in various cases (Figure 1), such as:

Case 1 involves the most direct type of linkage, where one stupa element has a specific name and semantic. This name and semantic combination is not used in any other elements. Additionally, when this element appears in other stupas, it will always have the same form.

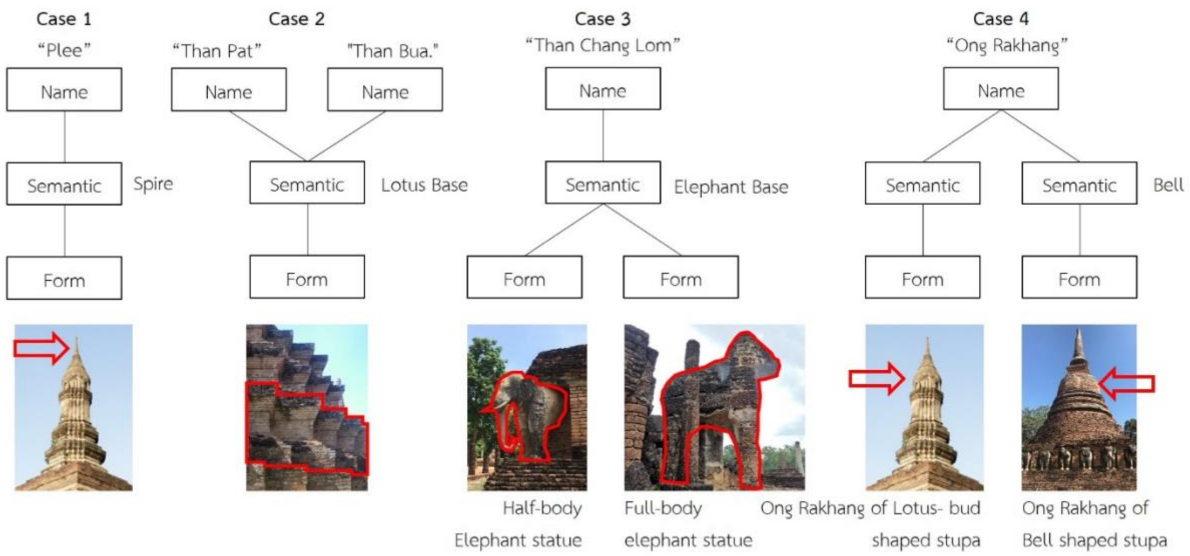
Case 2 occurs when the same element is referred to by different names. This type of case is common due to the diverse traditions within Thai artisan terminology. For example, the “Than Pat” (Lotus Base) could also be referred to as "Than Bat " or " Than Bua."

Case 3 occurs when the same name and semantic of a stupa element are used, but they have different forms. For instance, the “Than Chang Lom” (Elephant Base) may appear in one stupa as a half-body elephant, while in another stupa, it could be presented as a full-body. Despite the variation in forms, the Elephant Base in both stupas occupies the same position, serves the same purpose, and holds the same semantic.

Case 4 occurs when the same element name is used with different semantics, the positions of the elements on the stupas are different, and they have distinct shapes. For instance, an element named "Ong Rakhang" (bell) can appear in both bell-shaped stupa and the lotus bud-shaped stupa, but the bell element in these two stupas have different shapes, forms, and semantics, and they are situated in different positions on the stupas.

Figure 1

Complexity of the Ontology Structure Vary in Different Cases When Each Element Shares the Same Name, Semantic, or Form



METHODOLOGY

The framework in our research consists of the field data collection phase, the data development and management phase, the system development phase, and the system testing phase. Each phase is interconnected, as shown in figure 2.

Data Collection

We used high-resolution digital photographs taken with a Panasonic Lumix GH5 camera (22MP) and a Panasonic Lumix G 14mm f/2.5 ASPH lens (28mm in 35mm equivalent) to collect data, totaling 2,900 images. The table 2 provides the details of the number of images taken per stupa. We also measured the width of the base and the height of each stupa using a BOSCH GLM 50-27 CG laser distance meter.

Figure 2

Research Framework

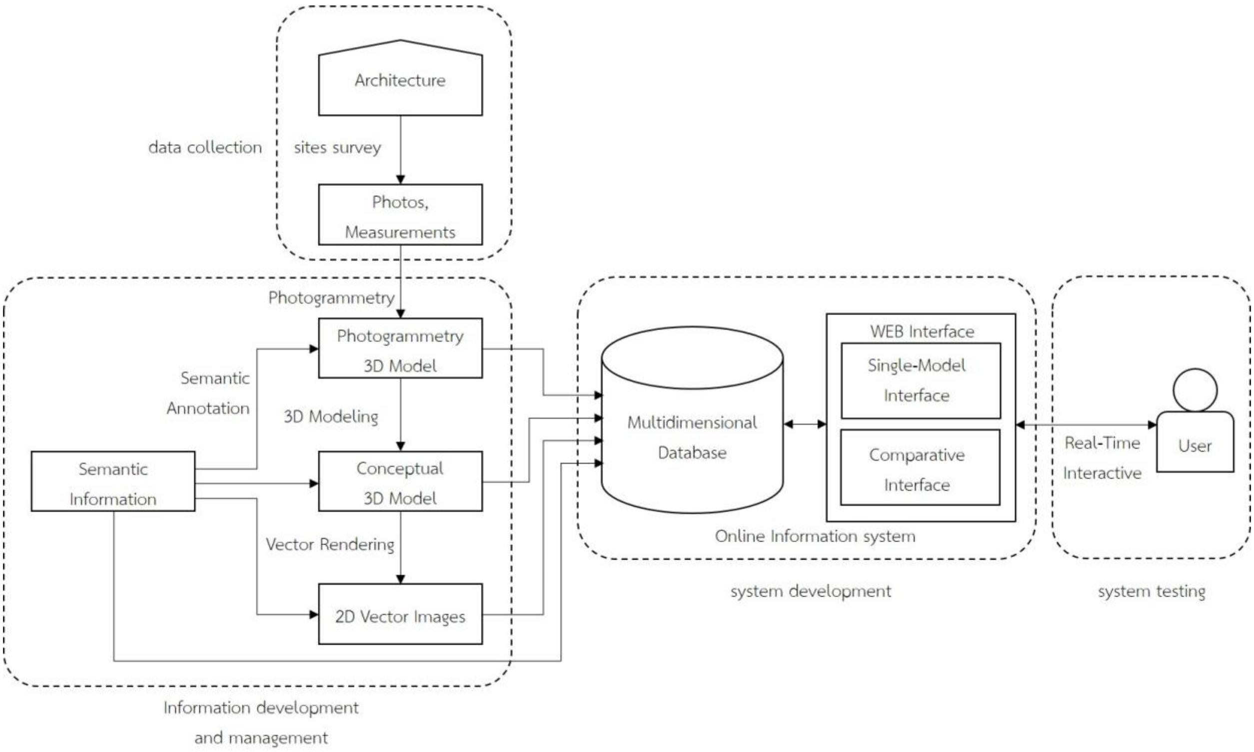


Table 2

The Number of Photographs Taken for Each Stupa

No.	Temple	Form	Photos
	Sukhothai		
1	Wat MahaThat	Lotus	136
2	Wat MahaThat	Bell	135
3	Wat MahaThat	Castle	83
4	Wat MahaThat	Lotus	90
5	Wat Chang Lom	Bell	128
6	Wat Traphang Ngoen	Lotus	145
7	Wat Chedi Sung	Bell	119

Table 2 (Continued)

No.	Temple	Form	Photos
Sukhothai			
8	Wat Sa Si	Bell	117
9	Wat Sa Si	Bell	118
10	Wat Tra Kuan	Bell	102
11	Wat Traphang Thong	Bell	96
12	Wat Chana Songkhram	Bell	103
Sri satchanalai			
13	Wat Chedi Chet Thaeo	Bell	146
14	Wat Chedi Chet Thaeo	Castle	102
15	Wat Chedi Chet Thaeo	Castle	94
16	Wat Chedi Chet Thaeo	Castle	84
17	Wat Chedi Chet Thaeo	Castle	92
18	Wat Chang Lom	Bell	133
19	Wat Khao Suwan Khiri	Bell	92
20	Wat SuanKaeo Uthayan Noi	Lotus	125
21	Wat Nangphaya	Bell	80
Kamphaeng phet			
22	Wat Phra That	Bell	83
23	Wat PhraKaeo	Bell	102
24	Wat Phra Non	Bell	96
25	Wat Chang	Bell	95
26	Wat Nong LangKa	Bell	102
27	Wat Ka Lo Thai	Lotus	133
Total number of photographs			2,931

Semantic Annotation of 3D Models

We used Agisoft Metashape software to create 3D models of the 27 selected stupas. The 3D files were imported into Autodesk Maya to adjust the scale to match the actual measurements, verify accuracy, and repair any missing polygons. Subsequently, we created low-poly conceptual models, referencing the shapes and proportions from the photogrammetry-generated models. In summary, we have two model options available for viewing: the 3D photogrammetric models and the low-poly conceptual models from 27 selected stupas, resulting in a total of 54 models (Figure 3). All of these models are uploaded to the Sketchfab platform for on-line visualization.

The next step is the segmentation and classification process based on architectural elements of the conceptual 3D models, followed by the procedure of linking each architectural element group to their respective semantic identification numbers in the database. In this context, we have opted to utilize the method of describing the architectural element of Thai stupa from Saising (2017) as the criterion for imparting semantics to the model.

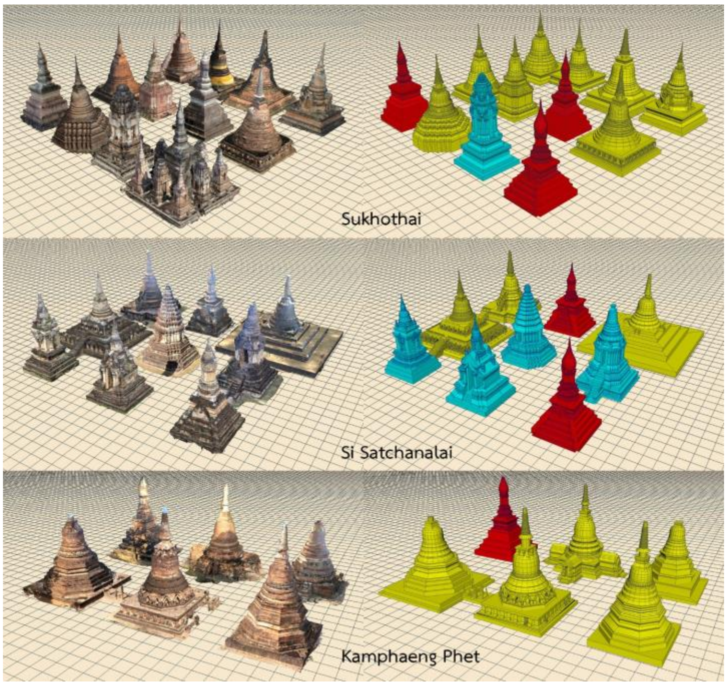
We have transferred semantic information from the 3D models to 2D images by generating orthogonal vector images (SVG) of the conceptual 3D models, using Autodesk Maya's vector rendering. These SVG images were generated from 3D low-ploy conceptual models with distinct identification numbers applied based on the architectural semantics. These numerical identifiers are inserted into the image in the form of an id attribute, which is used to label the groups of lines. These groups will be encapsulated within the <g> tag of the SVG code.

The result of this process is 2D vector images of all the stupa in the database, where each image is segmented, grouped, and connected with the semantic information of architectural elements.

The outcome of this process is a set of semantic enriched representations of stupas in both 3D and 2D forms. Each element is linked to an identification number associated with its semantics (Figure 4).

Figure 3

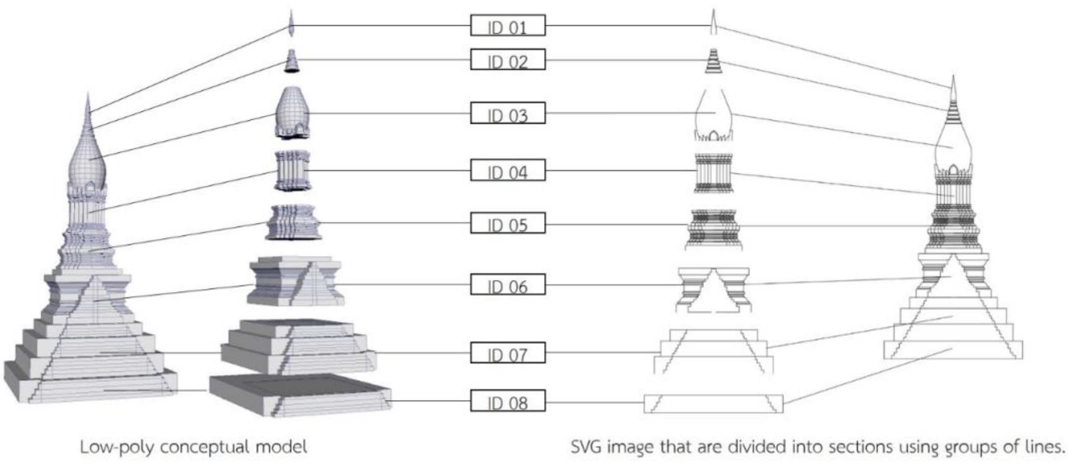
3D Models of 27 Selected Stupas, Found in 3 Historical Parks



Note. They can be categorized into three shapes*:* the *"*Rakang*"* or bell-shaped stupa (yellow)*,* the *"*Phumkhaobin*"* or lotus bud-shaped stupa*"* (red), and the *"*Prasat*"* or castle-shaped stupa (blue)*.*

Figure 4

Semantic Enriched Representations in 3D and 2D Forms



Database Development

The complexity of linking the attributes of the stupas as studied affects the design of the database system. The semantic information for each stupa must be stored in a diverse and comprehensive manner across all dimensions. Therefore, we have designed the database system to be divided into four tables as follows. (1) Stupa Table: This table stores relevant information such as names, descriptions, styles (e.g., lotus, bell, or castle), types (main stupa or secondary stupa), locations, photo filenames, and 3D model codes; (2) Elements Table: This table stores semantic information, the stupa ID numbers where the element appears, photos of the elements, and annotation codes; (3) Element Semantics Table: This table stores the main names and descriptions of the elements; and (4) Synonyms Table: This table stores other names used for the same elements with the same semantics. The relationships between these tables are illustrated in Figure 5.

System Architecture

The objective of this research is to allow the system users to compare the 3D shape and semantic information of architectural elements using three forms of stupas. Our system needs to present various formats, including 2D, 3D, and text, over an online interface, the system architecture has been developed using various languages. Each component is designed to work collaboratively through communication using specific commands. The architecture consists of:

1. An online interface primarily developed with PHP language, capable of presenting diverse architectural information of stupas, including:

- Displaying 3D representations using Sketchfab iframes
- Presenting vector graphics images of stupa elevations using SVG files
- Visualizing architectural element data with photos (JPG) and text
- Listing all selected stupa components with HTML buttons

2. A MySQL database used to store multidimensional data.

3. Communication between components of the user interface employs JavaScript commands and the Sketchfab API for development. As for interfacing with the online database, SQL is used (Figure 6). This communication occurs when system users interact with the 3D models (blue lines) or click on various interface buttons (red lines).

Interface Structure

The STUPA system is developed as two main components (Figure 7):

1. Stupa Model Selection Interface: This is the system's first page that presents basic information about our system and a list of all the stupas in the database. On this page, users can choose which stupa they are interested in viewing. They can also select the type of model they prefer (photogrammetric or low-poly conceptual model). Our system allows users to simultaneously view and compare up to three different models.

2. Main User Interface: This page serves as the main interactive interface for presenting various data of the selected stupas. The data that can be presented on this page includes 3D information, 2D vector and raster images, textual data, and a list of architectural elements of selected stupas.

From the "Model Selection Page," when users click the "Submit" button, the system will count the number of selected models. If it adheres to the specified conditions (at least one and up to three selected models); it will also send selected model identification numbers to the main user interface page.

In the main user interface page, the model identification numbers selected by the users from the previous page will be sent to this page in the form of an Array variable on the URL. The system will then determine and present an appropriate interface depending on the number of selected monument models. This interface will be divided into three or four sections, utilizing iframes. Each iframe embeds PHP pages for various architectural information presentations. These PHP pages cater to the diversity of architectural data (Figure 8), they are:

1. A page for presenting the selected 3D model. This page has a Sketchfab iframe embedded within it. When this page is accessed, users will be able to view the 3D model through the Sketchfab Viewer. Basic functionalities include navigating and rotating the camera within the 3D space and viewing the names of architectural elements by clicking on annotations. When a user clicks on an annotation on the model, the 3D camera will automatically move toward the selected element, and upon reaching it, the Sketchfab Viewer will present the element's name in a 2D Sprite format

2. A page for presenting the 2D vector image (in SVG format) of architectural elements. The vector paths are semantically organized into groups according to the architectural segmentation, such as "Pillars," "Lintels," "Pediments," and so on. Each group is labeled with a unique identification number.

3. A page for displaying the list of all architectural element semantics of selected stupas in HTML buttons. Within this page, an iframe will be utilized to provide additional details of the selected architectural elements, including photographs, names, and descriptions.

4. When the 3D page is loaded, the system will invoke the Sketchfab API using JavaScript commands to enable this page to display the 3D model through the Sketchfab Viewer. Subsequently, the identification number of the selected stupa's 3D model, obtained from the system's first page, will be verified within the SQL database to retrieve specific data, including its name, form, and 3D representation (photogrammetric or low-poly conceptual models).

Figure 5

Database Schema

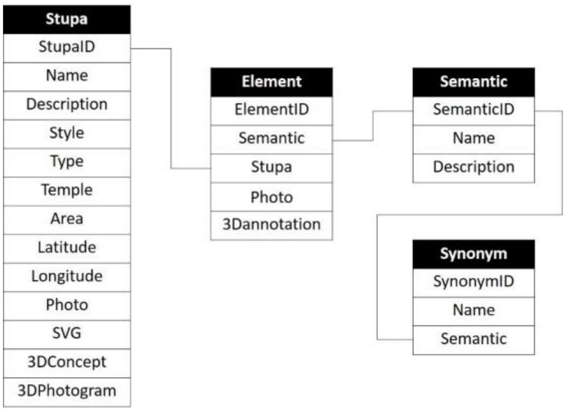


Figure 6

System Architecture

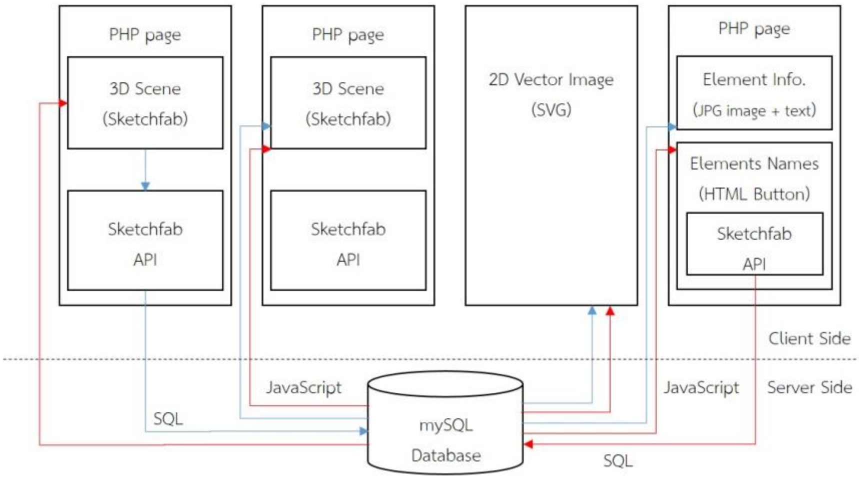


Figure 7

Developed System Interface

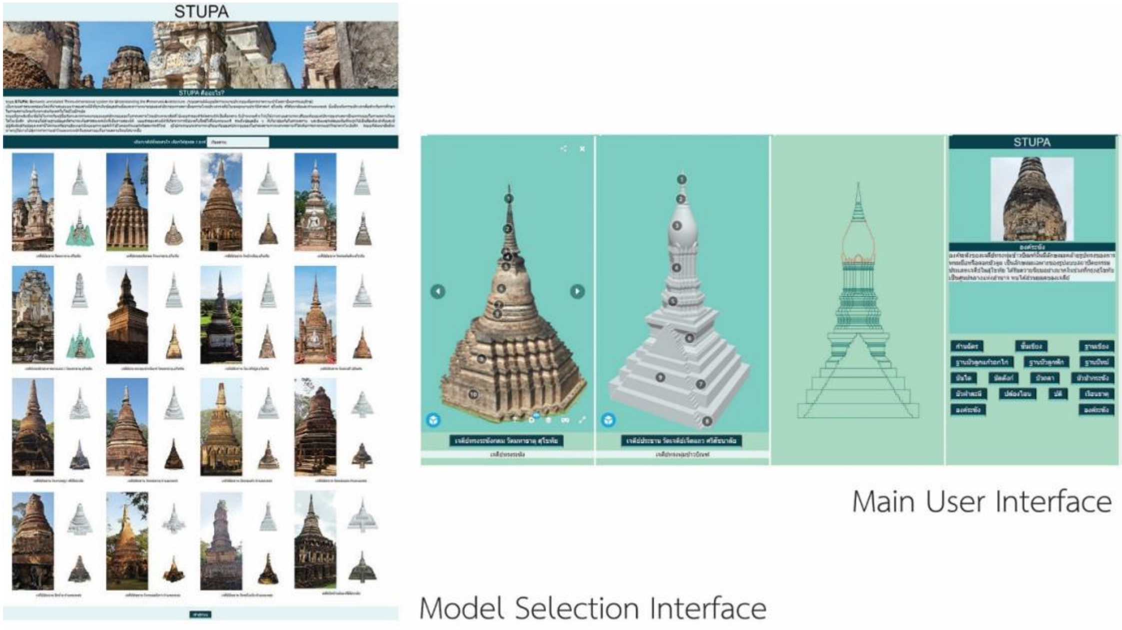
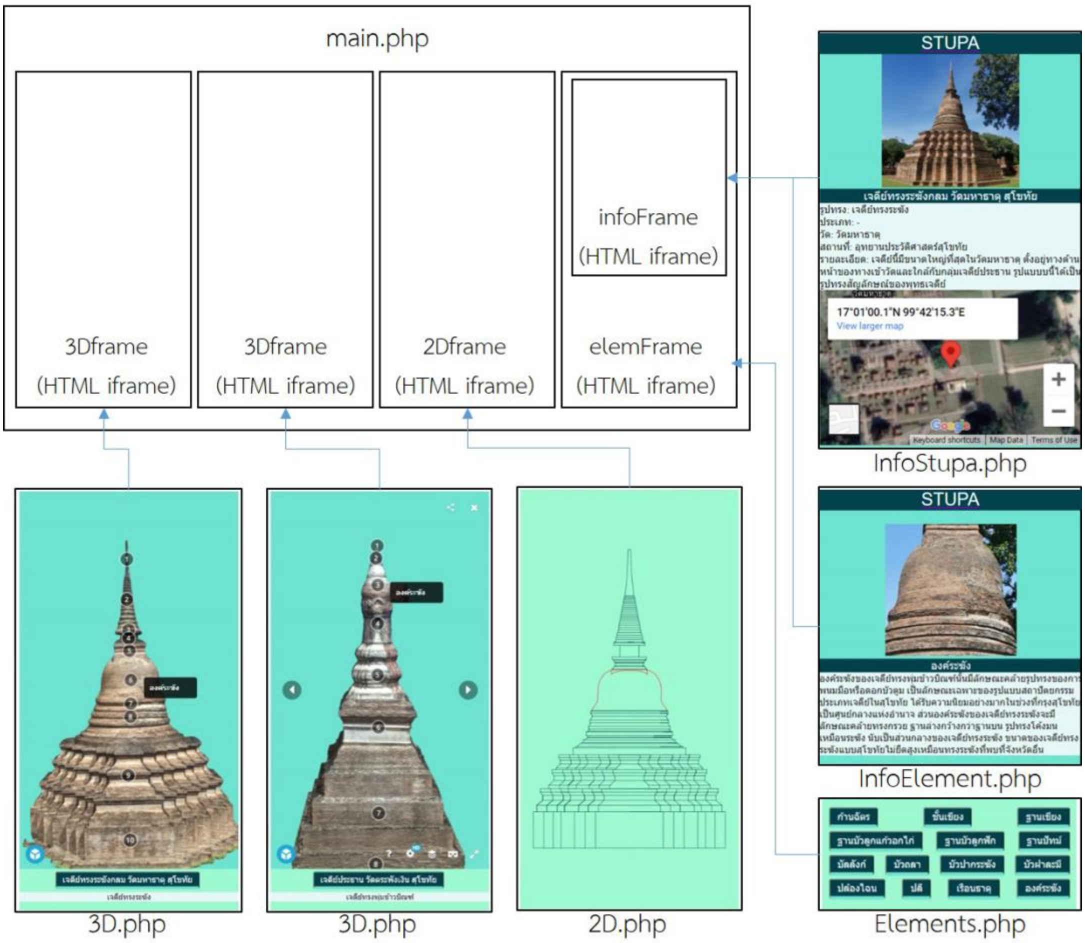


Figure 8

Interface Structure



System Development

Interactions within the STUPA system are established to allow communication between the presented 3D model and other components of the interface. This is achieved through the implementation of the Dynamic Sketchfab API. The moment that the user clicks on a Sketchfab 3D annotation, the PHP page communicates to three components of the system interface (Figure 9):

1. Communication with other 3D model interfaces (in cases where users select more than one stupa): Once the 3D page is loaded, the system will verify whether the other selected stupas have elements with the same names as the current page. If such elements are found, the system will establish relationships between the elements that share the same names. When a user clicks on an Annotation in one of the stupas, the 3D page will send a "gotoAnnotation" Sketchfab API command to the other 3D iframe. The cameras of other 3D models will automatically move towards the elements with identical names. Once reaching the targeted element, the Sketchfab Viewer will present the name of that element in the form of a 2D Sprite.

2. Communication with vector image of stupa elevation: When a user clicks on an Annotation, the system will send a JavaScript command to reopen an SVG image page. Then, the system will compare the unique identification number of the selected element with all of the vector elements present in SVG. Subsequently, the system will alter the color of the vector lines of the element group that shares the same identification number to red (Figure 10). This visual cue helps users understand the shape, form, and appearance of the selected element.

3. Communication with the detail information page: When a user clicks on an annotation, the system will send a JavaScript command to open the detail information page of the selected element. Then, it will use an SQL query to retrieve the photographic data, name, and semantic of the selected element from the database.

In addition to having interactions through clicking annotations on the 3D model, the developed system also allows users to directly select the names of the architectural elements to visualize both the 3D and 2D information of the selected elements. This functionality is presented in the form of buttons that can trigger actions to dictate to other interface components simultaneously. Each component provides feedback related to the selected element's name chosen by the user.

In addition to interactions through clicking annotations on the 3D model, the developed system also allows users to directly click on the names of elements to view both the 3D and 2D representations. This functionality is presented in the form of HTML buttons, each labeled with the name of the respective stupa element. Each button is capable of triggering JavaScript and Sketchfab API commands, along with sending the component's identification number to other components of the interface simultaneously (Figure 11). This enables the system to respond when the buttons are clicked. Each button can communicate with three components of the system's interface: (1) All the 3D models presented on the interface; (2) The vector image of the stupa's elevation; and (3) The detailed information page.

RESULTS

The STUPA System

Our developed system is created to facilitate the learning of names and semantics of Thai heritage architectures, specifically stupas, using 3D models as a medium. Its main goal is to enable users to compare architectural elements. The data within this system encompasses 2D images, 3D models, as well as other information related to the stupas within three historical park areas.

The current system includes both photogrammetric and low-poly conceptual models, providing users with a selection of a total of 54 models from 27 different stupas. Users can view and compare these stupas concurrently, with a maximum of three selected models. The system's interface is designed in three different layouts, based on the number of stupa models chosen by the user.

Figure 9

Communication Among Different Components Within the Developed System When Users Click on a 3D Annotation

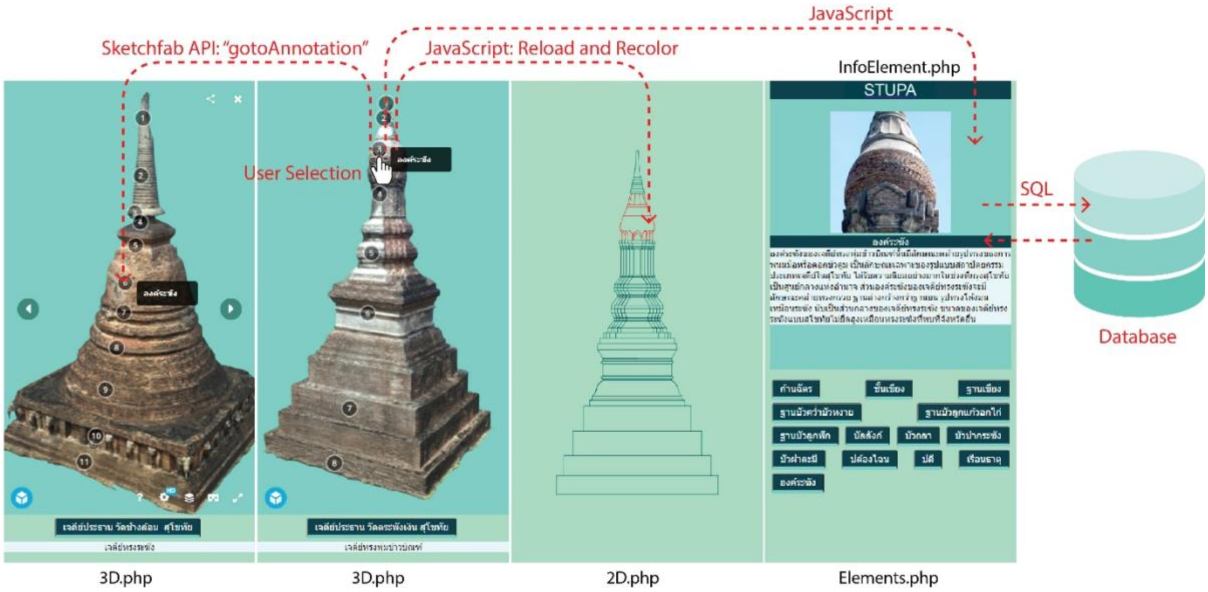


Figure 10

Selected Element Color-Changing Process in the Vector Image Using JavaScript Commands

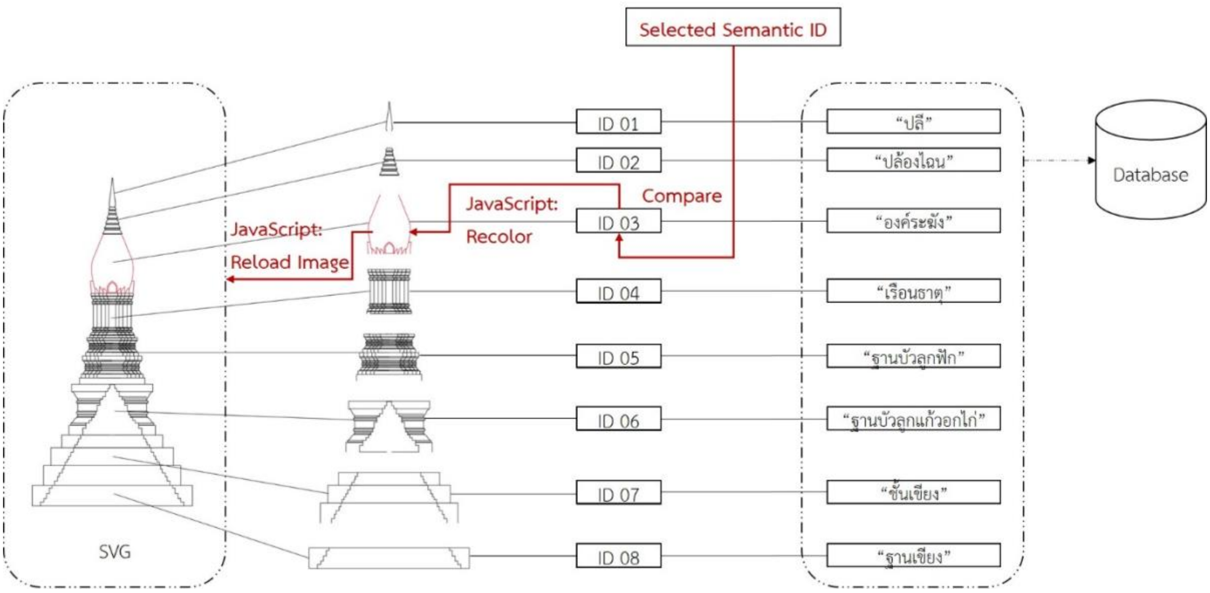
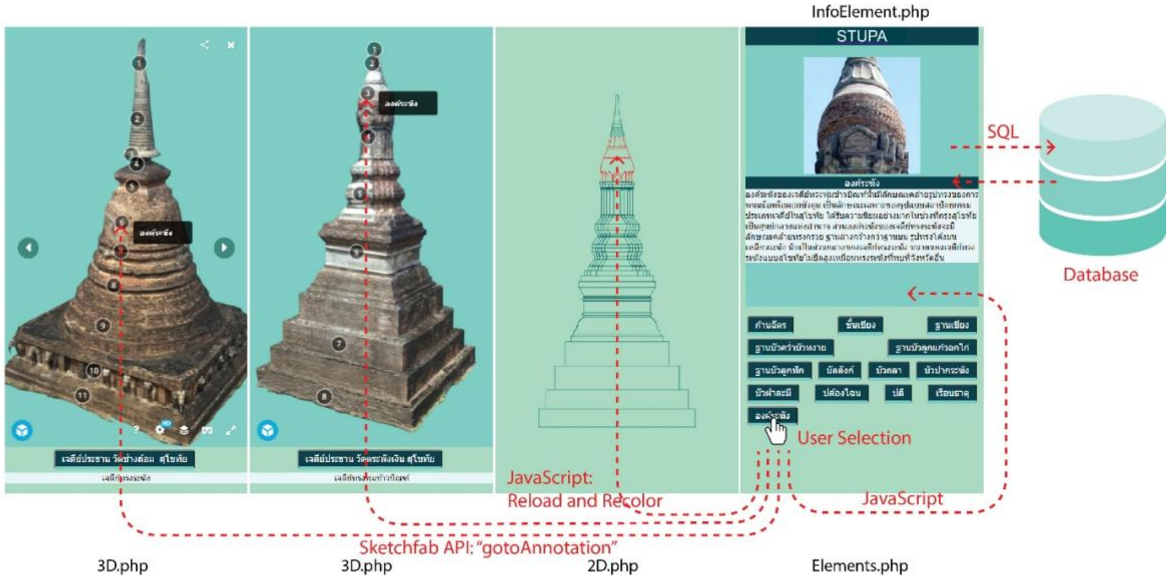


Figure 11

Communication Among Different Components Within the System When Users Click on an Element's Name Button



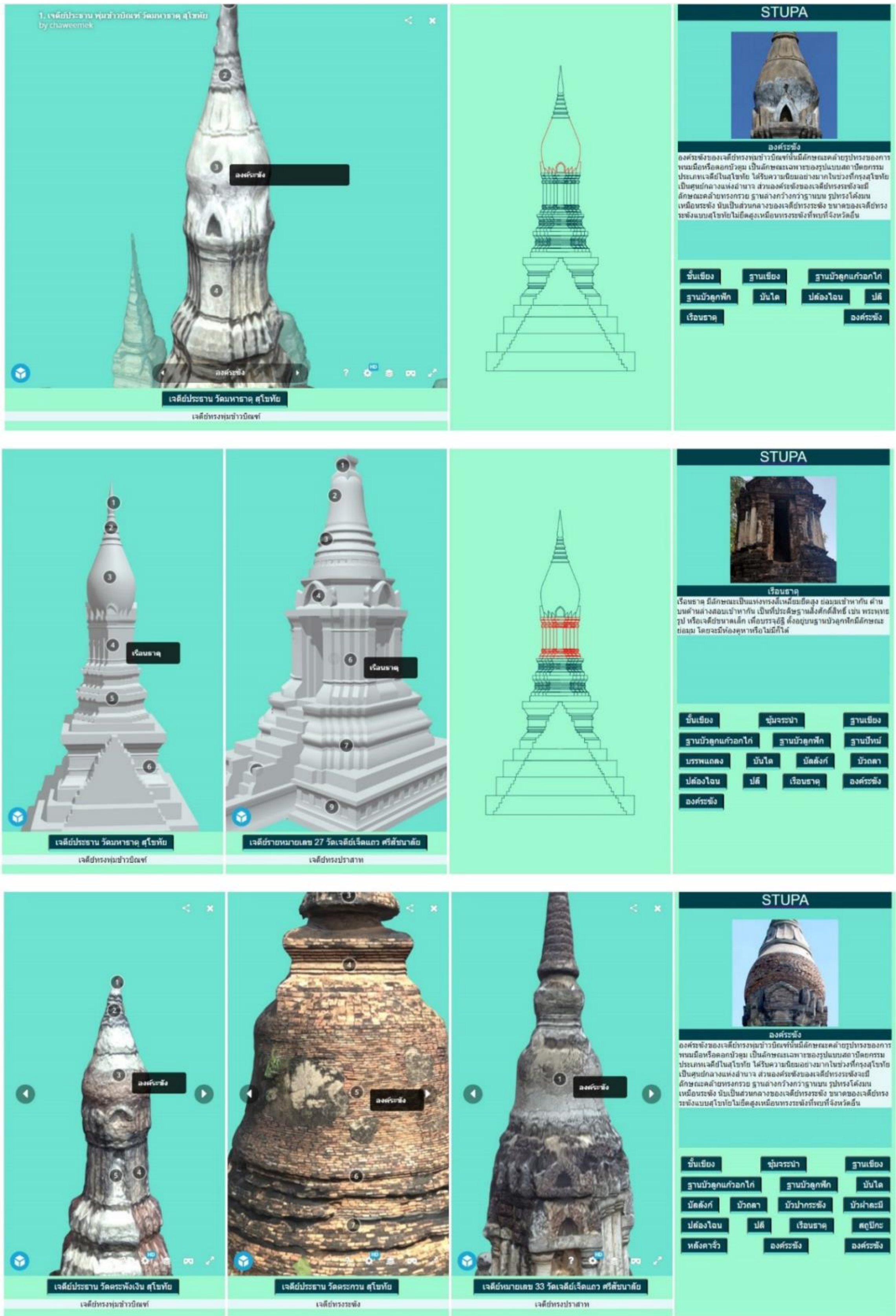
The interface for single model visualization will be divided into 3 sections to present the 3D model, the 2D vector image, and other relevant information related to architectural elements (Figure 12). This display method is designed to provide the clearest and most comprehensive representation of 3D information, particularly suitable for in-depth exploration of any individual stupa. When users click on elements of the stupa, whether through clicking on 3D annotations or architectural element name buttons, the 3D interface will automatically move the camera's point of view to the selected element. The selected element in the 2D vector image will changed to red. The element details section will display photographs, names, and descriptions of the selected element as well as clickable buttons listing all the architectural elements of the stupa.

The interface for two models is divided into four sections to present the 3D information of both stupas, the 2D vector images of stupa elevations, and the list of all the element's names appearing in both stupas (Figure 13). When users click on 3D annotations of either stupa element, the interface will automatically move the camera's point of view to the selected element with the same name on both models. If the component is only present in one stupa, the camera movement will only affect the one user interacted. Similarly, when users click on the element's name buttons, the camera will move accordingly.

In the 2D vector view, users have two options: viewing each stupa individually or displaying two stupas simultaneously. When viewing a single vector image mode, the stupa elevation view alternates based on user interaction with any of the 3D models. For the dual-vector image mode, elevation drawings of the two stupas are overlaid, and users can move the drawings freely to different positions, placing them side by side to compare dimensions, proportions, or angles of architectural elements (Figure 13). When users click on a component's meaning, the selected element in the vector view turns red, and a detail window displays a photo, name, and description of the selected element.

Figure 12

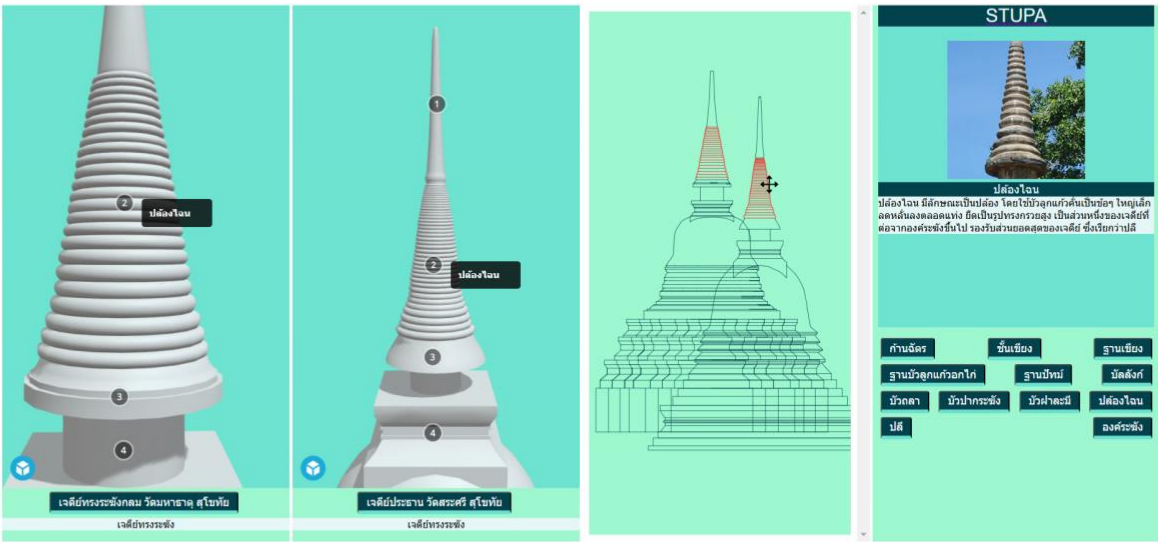
Comparison of the Developed System Interfaces in 3 Modes



Note. Single-model presentation (top), Two-model presentation (middle), and Three-model presentation (bottom).

Figure 13

The interface for viewing two stupas simultaneously with dual-vector image mode



This interface is designed to be suitable for comparing the differences in stupa elements. For instance, comparing the "Ong Rakhang" (bell) of the Rakang (bell-shaped stupa) with that of the Phumkhaobin (lotus bud-shaped stupa) to observe how even with the same name, their shapes and positions on the stupas differ. Or comparing variations of the same stupa such as the “Sum Choranum” (niche) of the Prasat (castle-shaped stupa), which can have both single and multiple niche types. Another example could be comparing elements with different names and forms that have the same semantic within the same stupa style, such as comparing the “Than Chang Lom” (Elephant Base) with the “Than Sing Lom” (Lion Base) of the bell-shaped stupa.

The interface for three models is divided into four sections. It presents 3D models and a list of architectural element names of the selected three stupas without 2D vector image (Figure 12). This interface is designed to be suitable for comparing diverse 3D forms. For instance, it could present all three forms of stupa within the experimental area: the bell-shaped stupa, the lotus bud-shaped stupa, and the castle-shaped stupa. Alternatively, users could also choose to view the same form of stupa across all three cases to understand the variations in each design.

All that has been mentioned above serves as an example of how the STUPA system we have developed can be used. In reality, users can choose how the system presents the 3D models according to their needs in different situations or contexts. The demonstration video for this system can be viewed at this URL: http://site001.ap.tu.ac.th/Stupa/demo.html.

Comparative Learning with STUPA: A Pilot Study

To assess the learning effectiveness of the developed system, we conducted evaluations through two distinct processes: (1) evaluation by target group students and (2) evaluation by experts in teaching Thai architecture.

Evaluation by target group students

This evaluation involved having a group of students engage in learning activities and then answer questions related to architectural elements in a test prepared by us. The participants were nine students from the Faculty of Architecture and Planning, Thammasat University, divided into three groups of three students each. They were exposed to three learning methods:

Method 1: *Learning with traditional 2D media* (*non-interactive*).

Method 2: *Learning with the developed system using a single-model interface*.

Method 3: *Learning with the developed system using a two-model interface for comparative learning*.

The participants underwent three rounds of learning, rotating through all three learning methods to study three different stupa forms. The order of each learning method will be alternated, with each method being used in the first, second, and third positions an equal number of times to avoid order effects, where the experience with one method might influence their performance in subsequent methods. They were allowed to spend as much time as they needed for each learning session, and we recorded the time taken for each.

The assessment process involved three rounds of testing:

Round 1: *Conducted immediately after each learning session, with questions about the three stupas that the students had just studied* (*testing short-term memory*).

Round 2: *Following the first test, with questions about three stupa forms that the students had not previously studied* (*testing understanding and application of knowledge*).

Round 3: *Conducted after 14 days, using the same questions as the first test, without prior notice to the students* (*testing long-term memory*).

Table 3

Average Score Table in Percentage From the 3-Round Evaluation, Involving Naming the Architectural Elements

1st assessment					
Learning method	Form of Stupa			Average score	Average time
	Lotus	Bell	Castle		
2D	85.25	88.95	77.85	84.02	5.12 min
Single-3D	84.50	90.14	80.85	85.16	7.25 min
Two-3D	83.74	88.65	79.88	84.09	8.10 min
2nd assessment					
Learning method	Form of Stupa			Average score	
	Lotus	Bell	Castle		
2D	32.75	35.38	37.14	35.09	
Single-3D	30.25	38.57	33.33	34.05	
Two-3D	65.35	68.52	67.77	67.21	
3rd assessment					
Learning method	Form of Stupa			Average score	diff.*
	Lotus	Bell	Castle		
2D	45.36	63.45	55.68	54.83	29.19
Single-3D	40.35	60.79	49.87	50.34	34.83
Two-3D	60.85	69.68	62.54	64.36	19.73

Note. *Scores decreased compared to the first assessment.

The first round of evaluation tested short-term memory. When the students engaged with all three learning methods, the results showed that the effectiveness was not significantly different. Students who used the comparative interface took the most time to learn. From interviews conducted after the sessions, it was found that students were most satisfied with the single-model interface. They expressed that they preferred studying architectural information in 3D rather than in 2D, and that exploring the components of one stupa at a time caused less confusion in memory retention compared to the comparative interface.

The second round of evaluation aimed to test understanding and the application of knowledge. We examined the scores from questions about stupas that the students had not studied before. It was found that students using the comparative interface scored higher. Upon inquiry, it was revealed that the students could use the similarities or differences in the stupa elements as preliminary information to guess the names and semantics of the elements, even for unfamiliar stupas.

The third round of evaluation tested long-term memory after a period of 14 days. It was found that students using the comparative interface showed the smallest decrease in scores. Upon inquiry, it was revealed that this interface allowed students to use memory and understanding of the shapes and names of the components more effectively than memorizing in a sequential and specific manner.

Evaluation by experts in teaching Thai architecture

This evaluation involved two experts testing the developed system as a teaching tool, followed by interviews. The experts expressed that the developed system has high potential for practical use in teaching. They suggested that the single-interface method is more suitable for student learning, while the comparative interface is better suited for teachers. The comparative interface allows for new teaching approaches, as it can highlight similarities and differences in architectural components more effectively than the single-interface method. This capability enables teachers to explain components in greater detail and can be used to teach a deeper understanding of architectural elements. Additionally, the experts recommended including stupa models from other historical periods to enhance the comprehensiveness of the teaching tool.

CONCLUSIONS AND DISCUSSION

Conclusion

This research has developed STUPA (Semantic annotated Three-dimensional system for Understanding Preserved Architectures), an online information system for learning the names and meanings of architectural elements of historical sites using a 3D model as an intermediary. The system comprises: (1) A database capable of storing information including 2D images, photogrammetric and low-poly conceptual 3D models, as well as other information related to selected sites; and (2) An interface designed for web use, enabling access and interaction with these data through the internet. This project utilizes 27 stupas within the historical park area encompassing Sukhothai, Sri Satchanalai, and Kamphaeng Phet as experimental areas. The system's development approach focuses on providing users the opportunity to compare and explore relationships between shapes, names, and semantics of architectural elements. This novel methodology sets it apart from other 3D online systems, particularly due to its ability to support the simultaneous viewing of more than one model. This system was developed with the purpose of serving as an educational tool for architecture students to learn the names and semantics of architectural elements, as well as an instructional media for experts in architectural heritage. The evaluation found that the developed system has high potential for practical use in teaching. The single-model interface is suitable for students to use for initial learning and memorization, while the comparative interface is better for understanding components in depth. This results in better long-term retention of information by learners.

Discussion, Limits and Perspectives

The STUPA system offers a novel approach to studying architectural semantics through a 3D online platform for comparing historical stupa elements. However, several factors could influence its conclusions:

Limited Dataset Scope: The system's focus on 27 stupas from three historical parks may bias results towards specific regional styles, limiting generalizability to other Southeast Asian architectures.

Manual Semantic Annotation: The reliance on manual annotation introduces potential inconsistencies, which could be minimized with automated or AI-driven processes for more reliable results.

Student Familiarity: Prior knowledge of Thai stupa elements may skew results, as more familiar participants may perform better, suggesting the need for a more diverse participant pool to assess the system's accessibility.

Alternative Interpretations: The system's effectiveness in improving retention may be more due to the novelty of 3D interactivity rather than the comparative feature itself. Testing against non-comparative 3D platforms could clarify this.

Small Sample Size: The limited participants may affect the robustness of conclusions, with a larger, more varied sample needed for a stronger analysis.

Photogrammetry and Low-Poly Models: While practical, these models may lack the detail needed for advanced study, making STUPA more suited for introductory learning rather than in-depth analysis.

In summary, while STUPA shows promise as an educational tool for comparative learning of architectural elements, the study's results may reflect specific contextual or methodological limitations. Addressing potential biases, such as expanding the dataset, automating annotations, and evaluating with a broader participant base, could further validate the system's effectiveness and ensure it meets diverse educational needs Here are the limitations of this research, along with perspectives for future improvements:

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