A Semantics and Data-Driven Biomedical Multimedia Software System

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Abstract—Developing a large-scale biomedical multimedia software system is always a challenging task: Satisfaction of sundry and stringent biomedical multimedia related requirements and standards; Heterogeneous software deployment and communication environments; and tangling correlation between data/contents and software functionalities, among others. This paper introduces a novel biomedical multimedia software system developed under Service-Oriented Architecture (SOA). Such a system takes the advantage of interoperability of SOA to solve the heterogeneity and correlation problems. The paper also classifies the system into services, annotation, ontologies, semantics matching, and QoS optimization aspects which may potentially solve the requirements problem: By establishing data ontology with respect to data properties, contents, QoS, and biomedical regulations and expanding service ontology to describe more functional and QoS specifications supported by services, appropriate services for processing biomedical multimedia data may be discovered, performed, tuned up or replaced as needed. Lastly, a biomedical education project that improves the performance of feature extraction and classification processed afterwards is introduced to illustrate the advantages of our software system developed under SOA.

Index Terms—SOA, Biomedical Multimedia Systems

I. INTRODUCTION

Developing a large-scale multimedia software system is always a challenging task: Such a system is usually characterized by intensive nature of multimedia data and inherent complexity among diverse multimedia data across heterogeneous platforms. Additionally, satisfactions of specific and stringent yet sundry biomedical related requirements (e.g., HL7\(^1\) standards, HIPAA\(^2\) policies, and FDA\(^3\) regulations) as well as satisfactions of functional and Quality of Service (QoS) requirements resulted from huge-sized multimedia data further increase the difficulty of software development. Even worse, such satisfactions also tightly correlate to the contents of biomedical multimedia data. In order to tackle the abovementioned requirements, heterogeneity and correlation problems, this paper presents a biomedical multimedia software system developed under Service-Oriented Architecture (SOA) [1, 2].

SOA is a cutting edge software engineering paradigm that provides a technical infrastructure for agile enterprises. Due to its interoperability and scalability advantages [1], SOA has gained increasing attentions in more than just business domain. Biomedical multimedia domain, among various disciplines advocating SOA, is an example that hopes SOA as their silver bullets for developing large-scale multimedia software system. A key rationale that SOA is suitable for biomedical multimedia software development is that “SOA relies on the business data and communication protocol headers that define the wire-level contract between partners; and to avoid the use of implementation-specific tokens for instance routing whenever possible [3].” Namely, different from traditional object-oriented software development that performs state-ful interactions by avoiding object references [3], SOA may not only solve the heterogeneity problem by decoupling the implementation and communication among different services but also provide a means to solve the correlation problem by routing business data and communication protocol headers to specific services.

For robustness reason, this paper classifies the system into five main aspects: (i) Services development for processing biomedical multimedia data. These services include, but not limit to, data analysis, data transmission, and data retrieval; (ii) Multimedia data annotations, comprising both automatic and manual annotations, will be supported to describe data/contents properties; (iii) Ontology building, learning and reasoning. Biomedical multimedia data ontology will be built by extracting and organizing data annotations. Service and domain ontologies will be also described. Learning and reasoning may be later applied to decision making for finding appropriate services; (iv) Service discovery and selection. Appropriate services will be discovered and selected based on the semantics matching among data, service and domain ontologies; and (v) QoS optimization. For a biomedical multimedia system to accomplish data analysis, transmission and retrieval tasks in compliance to specific use cases, orchestration languages [1] (e.g., WS-BPEL [3]) are needed to specify business process behavior based on services. However, many QoS are dynamically influenced by the data processed by services as well as the execution status and deployment environments of services at runtime. Introducing monitoring, learning, and adaptation mechanisms [2] may help tune up QoS or replace services dynamically. By

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1 Health Level Seven: http://www.hl7.org/
2 Health Insurance Portability And Accountability: http://www.hhs.gov/ocr/hipaa
3 Food and Drug Administration: http://www.fda.gov/
achieving the five aspects, it is expected that the introduced biomedical multimedia system developed under SOA will solve the aforementioned problems. Due to space consideration, this paper summarizes the five aspects and then specifically emphasizes on how our approach improves the results of analysis services introduced in a biomedical education project.

The paper is organized as follows: Related work is summarized in the next section; Section III introduces the proposed system, followed by a case study presented in Section IV; and finally, the concluding remarks and future directions are discussed in Section V.

II. RELATED WORK

Our work spans a wide spectrum of realms including requirements specific to biomedical domain, SOA for interoperability, and content-based image/video analysis, retrieval and transmission. Due to space consideration, this section presents the projects closest to us.

In [4], an SOA-based project for processing Chinese human genetic images is presented. Metadata and fuzzy query methods are introduced to improve retrieval performance. In [5], an SOA-based health care project is introduced. Such a project specifically concentrates on data transmission and integration in the realm of health care. Conversely, [6] presents an SOA-based project for statistically analyzing public health and biomedical data represented as XML documents.

As for architecture aspects, an architecture leveraging SOA technologies along with grid computing for national biomedical computation resource community is introduced in [7]. In [8], an enterprise data warehouse is developed based on the Veteran Health Administration’s information technology system. Such architecture is expected to meet the needs of strategic decision making for health care providers.

Lastly, modular ontology techniques for biomedical domain is presented in [9]. Such techniques offer ontology decomposition and composition for ontology reuse, ontology alignment, distributed and incremental reasoning, and scalable querying, to name a few [9].

As mentioned before, there is plenty of other related work focusing on different research challenges in the realms of SOA as well as biomedical multimedia and health care software systems. The objective of this paper is not to compete with the related work or present a “yet another system.” Conversely, as mentioned in Section I, this paper leverages the rationale of SOA and biomedical multimedia properties to solve the requirements and correlation problems specific to the biomedical multimedia domain.

III. OUR APPROACH

This section presents a biomedical multimedia software system following SOA.

Two major use case scenarios are described below:

(i) End users perform both manual biomedical multimedia annotations and light-weighted video segmentation analysis at the end users’ site. All the data will then be updated to the server’s site.

(ii) If an end user would like to request content based multimedia data retrieval by using the updated data from (i) or inputting new annotations for retrieving specific data, an orchestration language will be used to specify the business process behavior in the following order: (a) Annotation services will be needed for processing updated or new input; (b) Services for ontology building, learning and reasoning will be performed; (c) Semantics matching services will use quantitative and non-quantitative approaches to discover the most suitable analysis, transmission and retrieval service(s), given that these services have been developed, deployed and registered; (d) the orchestration language also defines the execution order of the selected services; and (e) the runtime environment of the orchestration language will bind and invoke the services and perform QoS optimization mechanisms. Each step in the use case scenarios will be explained in details in the following subsections.

A. Services for Multimedia Data

Because this paper only concentrates on the SOA for biomedical multimedia systems, services for such systems can be classified into analysis, transmission, and retrieval:

Analysis

The goal of analysis services is to develop data mining algorithms to discovery important patterns from biomedical multimedia data. Interesting analysis algorithms include:

(i) Object location identification; (ii) Video segmentation; and (iii) Video classification. For (i), tracking algorithms are expected to quickly identify the location of objects, predict the objects in the sequential frames, and handle the transformation and occlusion. Our system implements Kalman Filter algorithm to track the moving of an object class [10]. For (ii), because most multimedia data are of huge size, segmenting them into smaller and meaningful chunks may help improve throughput or other related QoS. For (iii), classifying biomedical multimedia data into different categories may foster better database management and retrieval.

In the proposed SOA, two types of segments will be investigated: video segments that contain similar objects; and video segments whose images may not contain the same objects but share similar context (i.e., “semantic segment”). A parsing paradigm and a video segmentation algorithm have been introduced in [11]. Video classification may provide better multimedia database management to support other services. Two of our current focuses are: medical video event classification using shared features [12] and audio-visual event classification via spatial-temporal-audio words [13]. The first service provides a promising classification strategy for multi-class video events, while the second one introduces a new representation of a video sequence (i.e., spatial-temporal-audio words) for classification.

Note that because video segmentation and video classification algorithms may also generate metadata as annotations for multimedia data, these implementations...
can be regarded as annotation services described in Section III-B.

Transmission

The objective of transmission services is to offer efficient, reliable and secure transmissions in compliance with SOA to guarantee high quality, low latency, and security of data delivery. Windows Communication Foundation (WCF) [14] provides a variety of transmission supports. However, such supports have to be configured by service developers at design time. For example, if an end user would like to submit a confidential skull image file to a remote site, he/she has no permissions to establish or re-configure the most appropriate transmission channel for the confidential data. In [15], transmission services are introduced – these services can be regarded as autonomous transmission providers to fulfill data’s requirements. For example, the six security modes (i.e., None, Transport, Security, Both, Transport with Message Credential, and Transport Credential Only) along with the reliable mode (i.e., Reliable Sessions) and different encryption algorithms are wrapped as transmission services. When specific transmission requirements are requested, candidate services may be selected at orchestration time or at runtime.

Besides, the system is focusing on developing services in the following three categories:

(i) Efficient streaming: (a) Unicasting: how to stream large size multimedia data while ensuring high quality and low delay; (b) Multi-path streaming: how to decompose multimedia data to multiple partitions of data streams and transmit each stream along disjoint paths. Three “Concurrent Transmission” services have been implemented in [15] to concurrently deliver segmented videos; and (c) Multicasting: how to transmit the same multimedia data to multiple users concurrently while maintaining sufficient bandwidth.

(ii) Secure streaming: Various security measures such as watermarking and its integration with efficient streaming protocols will be investigated.

(iii) Interactive streaming: When users make certain operations on the received video (e.g., scaling, rotation, forward, and backward), it is important that the server is aware of them and adapts its streaming session to accommodate, thereby significantly reducing the waiting time.

Retrieval

The objective of retrieval services is to efficiently assess large-scale biomedical multimedia databases using content based image/video retrieve algorithms [16]. However, due to a wide range of transforming, smoothing, and rendering, the same object in different videos may have totally different size, shape, and textures. How to design algorithms that are invariant to the object scale, illumination change, texture change, and transformation is a challenging problem.

Our current focus is to investigate algorithms that can handle shape invariance, introduce new similarity measurements, and extend the measurements to handle other variances (e.g., texture and illumination changes). The future plan is to introduce adapters to embrace existing work surveyed in [16] into our system.

Again, although there are only three types of services investigated, the loosely coupled design of autonomous services, interoperable message communications, and commonly agreed standards utilized in this system allow new services to be added and orchestrated easily in the future. All existing and new services should be described properly by WSDL [3], including their input and output formats, functionality provided, standards/policies/regulations followed, and QoS properties, to name a few. Finally, analysis and retrieval services are usually considered as a joint component in the content-based image retrieval community. Our system decomposes them because of the definition of “service” [1]. Such services can be easily composed together and considered as a single aggregator/composite service under our system following SOA principles.

B. Multimedia Data Annotation

In order to better annotate biomedical multimedia data, our system classifies biomedical multimedia annotations into four categorizes: data properties, contents, QoS annotations, and regulations.

Data Property Annotations

Data properties describe physical attributes of the data instead of the contents of the data. They can be further classified into text, audio, video and image properties. The followings are some example attributes used:

(i) Text Properties: file name, file size, file format, created date, last modified date, font, and font size.

(ii) Audio Properties: file name, file size, file format (e.g., mp3, .avi), created date, last modified date, duration/length, bit rate, sample rate (e.g., 44Hz), channels, and layer.

(iii) Video Properties: file name, file size, file format (e.g., MPEG-2, .flv), created date, last modified date, duration/length, resolution, number of frames, number of streams, average bit/second dedicated to a video stream, width, height, and supported players.

(iv) Image Properties: file name, file size, file format (e.g., .bmp, .jpeg), created date, last modified date, width, height, pixel format, and resolution.

Content Annotations

Content annotations using image/video content analysis have been an important topic for years. Annotations are obtained by either performing analysis services (e.g., video segmentation and classification) to automatically generate useful analysis results or manually updating useful content information. Important automatic and manual annotation approaches for images and videos can be respectively found at [17] and [18]. Our current status is introducing a MPEG-7-based manual annotation portal adapted from the Caliph & Emir project [19].

http://www.w3.org/2005/Incubator/mmsem/XGR-mpeg7/
portal provides an interface to annotate data, contents, QoS, and regulations. Investigating new automatic annotation services or introducing adaptors for existing work in [17, 18] to fit into our system is our future work.

**QoS Annotations**

In order to solve the data/content-service correlation problem, QoS requirements for data and contents should be also annotated. For example, if a skull image is expected to be transmitted to a remote site in a secure way, QoS annotations (e.g., minimum requirements of encryption algorithms) for such an image should be described. With QoS annotations, discovering and selecting appropriate services configured by WCF or Java EE 5 [20] platforms may be easier. An interface that allows users to manually input QoS and Regulation annotations (described next) has been introduced in [15]. For security options, users can determine the security level of data from six security modes provided by WCF. Similarly, reliability, latency, and segmentation requirements can be also decided based on data’s needs. If users provide insufficient or incorrect QoS requirements information, reasoning about most appropriate QoS by using other annotations available in the data ontology is desirable.

**Regulation Annotations**

The message development framework introduced at the HL7 website (http://www.hl7.org) follows HL7 standards to guarantee high quality messages exchange in healthcare environments. Such a framework is implemented using the object-oriented paradigm. Because most of the users of biomedical multimedia systems have biomedical background and may know specific standards to follow, manually annotating biomedical regulations for multimedia data is also introduced in our SOA: If data to be processed require to follow specific and stringent HL7 standards, HIPAA policies, and FDA regulations, the services to be selected for data process also need to follow them.

Annotating data, contents, QoS and regulations is our first step for orchestrating biomedical multimedia systems out of appropriate services. Such a step can be treated as data requirements elicitation either by automatic analysis services or by manual end user input. It can be also regarded as an extraction step “that supports acquisition of domain ontology from textual sources [21].” Followed by annotations, ontology building is the next step.

**C. Ontologies**

“Successful employment of semantic Web services depends on the availability of high quality domain and service ontologies [21].” Building high quality domain ontology requires following features: *generic* enough to be used in many service descriptions; and *rich* enough to describe the complex relationships existing in a specific domain [21]. Some existing ontology learning frameworks and tools have been introduced to establish domain ontology from textual sources (e.g., TextToOnto [22]), and others may use visual editors/frameworks to construct ontologies (e.g., Protégé [23]). For example, domain ontology for HL7 has been created using Protégé [23]. Protégé also provides reasoning API to help infer logical consequences from ontologies. A number of other ontology learning techniques (e.g., statistical-based, rule-based, and hybrid) have been comprehensively surveyed in [24].

For building service ontology, OWL-S [25] has been widely applied to describe service semantics, which facilitate service discovery, composition and invocation. Because of the correspondence between OWL-S and WSDL [3], XSLT can be used to transform from OWL-S to WSDL or vice versa. Note that because our system specifically concentrates on using data ontology (introduced later) to discover and select most suitable services based on service and domain ontologies, the expandable serviceParameter and serviceCategory profile attributes of OWL-S should offer sufficient information (e.g., the HL7 standards supported by and Quality Rate provided by a service), so that semantics matching among the three ontologies for the discovery and selection purpose can be achieved.

Besides service and domain ontologies, this paper introduces data ontology extracted from multimedia data annotations described in Section III-B. Because multimedia data annotations are mainly described by textual sources (e.g., natural languages or XML from MPEG-7), the tools, frameworks, and techniques introduced in [2, 24] may be also used to build data ontology. We are working on adapting some open source ontology building, learning and reasoning frameworks or tools into services that can be deployed in our system.

**D. Semantics Matching**

As mentioned before, one of the objectives of OWL-S is to facilitate service discovery. With expandable serviceParameter [25], more informative functional and QoS properties and constraints that a service can provide or is limited to can be described. For example, an analysis service may describe maximum file size and file formats it can process. Also, this service may mention the specific kinds of contents it can track/segment/classify and if the contents should be audio-enabled or not. Lastly, a transmission service may describe specific encryption algorithms it provides. Conversely, data ontology comprises the elicited “QoS requirements” as well as data and content properties of biomedical multimedia data either from users or analysis services. Such information can be used to match the semantics of a service described in serviceParameter.

For quantitative matching (e.g., latency), mathematical formulae computed along with the directions of a flowchart under given constraints are the most popular approaches (e.g., [26, 27]). For non-quantifiable matching (e.g., security) among data, service and domain ontologies, semantics matching with ontology learning and reasoning described before may be more suitable. For example, supposed a biomedical multimedia video that

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5 XML Transformations: http://www.w3.org/TR/xslt.html
describes a fruit fly’s flying motion requires a reliable HL7 message transmission, the semantic reasoning engine may infer to the most appropriate transmission and analysis services.

Some technical issues worth mentioning are: (i) Inference rules for semantics matching are very domain-specific. Namely, each biomedical multimedia domain (e.g., digital forensics vs. cell biology) requires its own inference rules and mathematical formulae to select the most appropriate service(s); (ii) There might be more than one suitable service to be selected. Services selected based on quantitative approaches may be ranked based on the computation results. For those services selected based on semantics matching, ranking of those services should be determined with the help of domain experts. Even worse, such ranking results may be applied case by case instead of just based on a specific domain; (iii) For both quantitative and non-quantitative matching, various functional and QoS properties may be weighed differently based on the importance to specific domains. How to express such importance into specific inference rules is a challenging task; and (iv) A service usually has more than one associated serviceParameter and these parameters may also have orthogonal or non-orthogonal associations [28] between each other. How to introduce and manage such tangled relationships is difficult.

E. QoS Optimization

In order for a biomedical multimedia system to accomplish data analysis, transmission, and retrieval in compliance to specific use cases, orchestration languages [1] are needed to specify business process behavior based on services. However, there might be more than one suitable candidate service. Also, QoS offered by a service are influenced by multimedia data, internal resource status and external deployment environments [29]. Lastly, business/system/application requirements are ever changing and candidate services may not be available.

All of the above factors suggest that either the runtime environment of orchestration languages (e.g., [30]) or business processes (e.g., [31]) should be extended to support QoS monitoring, learning and adaptation as well as dynamic service replacement [30]. Our past work [29] introduced dynamic service adaptation by intercepting the Just-In-Time compilation events under the .NET platform. This is more a business process-related extension. Currently, our focus is to expend the runtime environment to introduce suitable mechanisms specific to the biomedical multimedia domain.

IV. A CASE STUDY

In [15], six transmission services are introduced along with their experimental results. Such services overcome WCF’s design-time configuration problem and allow dynamic adaptation by orchestration languages. This paper focuses on analysis services implemented under SOA, which are further explained in details along with a medical education project.

A. Background of the Medical Education Project

An example to illustrate our approach is shown in this section. The goal is to automatically classify a given medical video clip into one of the video event categories, such as physician’s presentation, diagnostic procedure, and surgery procedure. Our focus is the educational medical videos, which have been widely used in schools and hospitals for the training of medical students, residents, and fellows.

Generally, an educational medical video starts with introductory images. These images summarize the main content of the video and they are usually presented by a third party anchor. We call this kind of video segment as “General Introduction” event. The majority of the images in this event are natural images such as the hospital building in the urban scene, or hospital room in the indoor scene. Some example images in this event are shown in the first row of Figure 1. After the “General Introduction” event, the video may show the presentations by the physicians. The physicians introduce the overview of the medical procedure, as well as the explanations of some technique concepts related with the procedure. We define this kind of video segment as “Presentation” event. The images in this event are usually individual physician’s image captured from different view angles. These images are illustrated by the second row of Figure 1. Another type of images that often appear in the educational medical video is the conversations among physicians and patients. Images in this type of event include the interactive scenes such as chatting between the physician and the patient. We define this type of video segment as “Conversation” event. The third row of Figure 1 illustrates this event. The images in the fourth row of Figure 1 show some example images for “Surgery” event. Usually, the images in this event include multiple people (e.g., surgeons, nurses, and patients) and objects (e.g., operation table, instrument, and etc.). The major challenge of medical video event categorization is that the content variations among different types of images are huge due to the large variety of medical procedure, human anatomies, and medical devices.
B. Three-Step Approach

To solve the challenges of content variations, a three-step approach that follows the first use case scenario described in Section III is introduced. Such an approach consists of pre-processing step, feature extraction step, and classification step, each of which is regarded as a service in our SOA-based system. The insights gained during the pre-processing step can be used to guide the following two steps. As mentioned before, the content variations among the images of medical videos are huge. If the common characteristics for each video category can be learnt to guide the following steps, the performance may be potentially improved.

The feature extraction step and classification step are similar to many existing solutions for video event detection. Feature extraction service is a procedure of transforming the input data into a reduced representation set of features. It is expected that the extracted features will contain the relevant functional and/or QoS information in order to perform the desired task using the reduced representation instead of the entire input data set. Classification service is a procedure to place the individual item (in our context, the item refers to the video clip or video segment) into groups. The classification decision is based on two important aspects: (i) the quantitative characteristics of the features extracted from the individual; (ii) and the training sets used for building the classification model.

Different from existing approaches, the service selection of feature extraction and classification are partially determined by the analysis results from the first step (i.e., pre-processing step). The goal of the pre-processing step is to perform light-weighted analysis and obtain the insights of the data sets. The insights gained from this step will be used to guide the following two steps (i.e., feature extraction step and classification step). This idea is hinted by the basic principle of Machine Learning (ML) research: A large number of training sets are employed to build a sophisticated classification model and this model will be used for classifying new data set. Different from the typical learning procedure in ML research, a small number of data sets are used and no mathematical or statistical model is built. Instead, a light-weighted analysis is performed to gain some basic understanding about the visual features for different type of video categories. This type of understanding provides the guidance for further processing.

Specifically, the methods of light-weighted analysis in our pre-processing step include: edge detection (i.e., edge refers to the points where there is a boundary (or an edge) between two image regions), corner detection (i.e., corner indicates the point-like features in an image, which have a local two dimensional structure), and salient points detection (i.e., salient point refers to location in an image where there is a significant variation with respect to a chosen image feature). There are a few reasons for us to choose these algorithms. First, all the three algorithms are light-weighted, which means the computation resources required by these algorithms are relative small. Secondly, each algorithm could produce different results for images from different medical procedures. This is a desirable property, because our ultimate goal is to differentiate the videos into different categories. Thirdly, the conclusions drawn from applying the simple algorithms to different images can guide us the services/service combination for the following two steps. For example, “edge detection” method excels other methods for images that belong to “Presentation” video category. This is shown in Figure 2. This result indicates that the flow-based methods [32-34] (i.e., flow-based methods operate directly on the spatial-temporal sequence without segmentation. The specified pattern can be recognized by brute-force correlation) should be pursued for the next two steps due to its QoS. The corner detection can produce the best results for the images in the “Conversation” category while salient points detection works best for images in “Surgery” type. Figures 3 and 4 illustrate the results of corner detection and salient points detection results for “Conversation” and “Surgery” images, respectively. Our experiments for the “General Introduction” video category show that the corner detection produces the best results for this category. These results suggest that tracking-based methods [35-37] (i.e., the methods follow the moving of the object and segment the objects of interests from the background. The trace of the model parameters are generated by tracking the movement of the object over time. The generated trace is compared with the target spatial-temporal pattern to determine the video event) may be a good fit for “Conversation” images and “General Introduction” images; and space-time interest points approaches [38-41] (these approaches extend the traditional spatial interest points detection techniques to spatial-temporal domain for video event detection) may be suitable for “Surgery” images.

To summarize, the medical education project shows that the three-step approach solves the correlation problem: It utilizes business data (i.e., analysis results from the previous step) to route to suitable subsequent services (e.g., corner detection or salient points detection). Namely, the analysis results from previous step are stored in data ontology, which is used to match service ontology. Then appropriate service(s) for subsequent step(s) could be discovered. As for the heterogeneity problem, wrapping data into SOAP or using REST-ful approach [42] to perform interoperable message communications among heterogeneous platforms or services may solve such a problem. Lastly, similar to the solution of the correlation problem, the requirements problem might be partially solved by the three-step approach if QoS could be extracted. However, to solve the requirements problem comprehensively, other services (e.g., annotation, semantics matching) need to be involved, which will be our future work.

V. Conclusion

This paper introduces a novel biomedical multimedia software system with a case study developed under SOA. Such a case study introduces three analysis services (i.e., three-step approach) to illustrate the advantages of
Due to space and time consideration, this paper only summarizes some ongoing and completed work of each aspect and introduces a case study involving analysis services. Currently, all the five aspects are being continuously improved with new features/algorithms. Several existing frameworks, tools, and techniques are also investigated. Our hope is to introduce adapters so that these existing artifacts can be reused and deployed in our SOA-based system.

REFERENCES


BIOGRAPHY

Dr. Shih-Hsi “Alex” Liu is currently an assistant professor in the Department of Computer Science at the California State University, Fresno. He received his B.S. degree at National Chiao-Tung University, Taiwan in 2000 and M.S. degree at University of Houston in 2002, both in computer science. Dr. Liu’s primary research interests are in software product line engineering, model-driven engineering, domain-specific languages, service-oriented computing, and evolutionary computations. His research work has been published in the journals, book chapters, and refereed proceedings and he has co-organized or committed in journals/conferences/workshops in the aforementioned areas. Dr. Liu is a member of ACM, ACM SIGAPP, ACM SIGSOFT, ACM SIGCSE, IEEE, and Upsilon Pi Epsilon.

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