Introduction

Historical Roots and General Overviews
Spatially Explicit AI Models
Spatial Representation Learning
Spatial Prediction and Interpolation
AI in Cartography and Mapping
Deep Learning in Earth Observation
GeoAI in Social Sensing
Geospatial Semantics and Geo-Text Analysis

Introduction

Nowadays artificial intelligence (AI) is bringing tremendous new opportunities and challenges to geospatial research. Its fast development is powered by theoretical advancement, big data, computer hardware (e.g., the graphics processing unit, GPU) and high-performance computing platforms that support the development, training, and deployment of AI models within reasonable amount of time. Recent years have witnessed significant advances in Geospatial Artificial Intelligence (GeoAI), which is the integration of geospatial studies and AI, especially machine learning and deep learning methods and latest AI technologies in both academia and industry. GeoAI can be regarded as a study subject to develop intelligent computer programs to mimic the processes of human perception, spatial reasoning, and discovery about geographical phenomena and dynamics, to advance our knowledge, and to solve problems in human environmental systems and their interactions with a focus on spatial contexts and roots in geography or geographic information science (GIScience). Thus, it would require the knowledge of AI theory, programming and computation practices as well as geographic domain knowledge to be competent in GeoAI research. There have already been increasingly collaborative GeoAI studies for GIScience, remote sensing, physical environment and human society. It is a good time to provide a key reference list for educators, students, researchers, and practitioners to keep up with the latest GeoAI research topics. This bibliographical entry will first review the historical roots for AI in geography and GIScience and then list up to 10 selective recent works with annotations that briefly describe their importance for each topic of interest in the GeoAI landscape, ranging from fundamental spatial representation learning to spatial predictions and to various advancements in cartography, earth observation, social sensing and geospatial semantics.
Historical Roots and General Overviews

The intersection of AI and geographic studies is not completely new and has its historical roots as described in Smith 1984; Couclelis 1986; Openshaw 1992; Openshaw and Openshaw 1997; and Janowicz et al. 2020. Before the recent explosion of deep learning studies by LeCun et al. 2015, major AI development including theoretical speculations in the 1950s and 1960s (see Buchanan 2005); artificial neural networks (ANN), heuristic search, knowledge-based expert systems, neurocomputing and artificial life (e.g., cellular automata) in the 1980s; genetic programming, fuzz logics, and development of hybrid intelligent systems in the 1990s; as well as ontology and web semantics for geographic information retrieval (GIR) in the 2000s all together contribute to the research themes of GeoAI. One key question that drives the contribution in GeoAI is why spatial is special in AI. One answer might be because geographic location is often the key for linking heterogeneous datasets that have been intensively used for training advanced AI models (more information in Hu et al. 2019a). In addition, what are the key geographical questions that we can now address better using AI than traditional approaches? What are the unsolved problems can now be solved with AI? Are there any new theories or intelligent approaches to building models and data pipelines in geographic information systems (GIS)? Geographers and computer scientists have made great efforts on contributing to these topics in recent publications such as in a special issue on Artificial Intelligence Techniques for Geographic Knowledge Discovery for International Journal of Geographical Information Science by Janowicz et al. 2020 and in the ACM SIGSPATIAL GeoAI workshops (2017,2018,2019) by Hu et al. 2019b, as well as discussions in the American Association of Geographers (AAG) GeoAI and Deep Learning symposiums (2018,2019,2020).


Profound thoughts in philosophy, fiction, and imagination and early inventions and technology advancements in electronics, engineering, and many other disciplines have influenced AI.


A high-level review from worldwide lead researchers on deep convolutional neural networks and recurrent neural networks that have brought about breakthroughs in processing images, video, speech and audio.


It summarizes the applicability of AI to geographical problem solving, research and practices with a focus on individual and aggregated intelligent spatial decision-making from both cognitive and engineering perspectives.

It broadens the discussion of AI in geography after Smith (1984) from more theoretical dimensions of the computational approach and introduces the discrete-structure hierarchy as a universal framework for multilevel analytical representation.


Key landmarks in the development process of AI tools for spatial modeling and analysis in GIS may include: (1) demonstrations of new technology with pedagogic data support; (2) empirical evidences that new AI methods outperform traditional approaches; (3) new methods work in data rich environment in GIS; and (4) incorporation of AI procedures in general analysis and modeling.


It is a milestone book project in GeoAI and introduces key principles of AI with applications in geography, urban planning, and GIS. It mainly covers the contemporary AI methods and technologies in the 1970s-1990s, including heuristic search, expert systems, intelligent knowledge-based systems, neurocomputing, ANN, artificial life, genetic algorithms, and fuzzy systems.


It reviews state-of-the-art research on GeoAI for geographic knowledge discovery, explains how a change in data culture is fueling the rapid growth of GeoAI, and points to future research directions. It also calls for the development of spatially explicit models and the sharing of high-quality geospatial datasets for advancing reproducible GeoAI research.


It reviews the research articles published in the 2017, 2018, and 2019 SIGSPATIAL GeoAI workshops and summarizes a wide range of topics, such as geospatial image processing, transportation modeling, public health, and digital humanities. A list of GeoAI research directions is also suggested.

It reviews recent developments of AI in geospatial studies with a focus on machine learning and deep learning approaches and introduces a variety of applications such as automatic recognition of natural terrain features from remote sensing images, land cover classification, and spatiotemporal habitats modelling.

**Spatially Explicit AI Models**

The location uncertainty, spatial heterogeneity and dependence along with other spatial characteristics in geographic information make spatial thinking and the use of spatial concepts as the first citizen when developing spatially explicit AI models (More information can be found in Kuhn 2012; Zhu et al. 2018; Janowicz et al. 2020.) Therefore, the integration of AI technologies and methods with geography and GIS is not a one-way street. Location is a key to integrate and synthesize multi-source data layers; geographic domain knowledge and spatial concepts contribute to the development of different contextual spaces (i.e. mobility space and social space) and play an important role in the development of AI models. Being a spatially explicit model requires to meet one of the four spatial tests (see Goodchild 2001; Janowicz et al. 2020): (1) invariance test, (2) representation test, (3) formulation test, and (4) outcome test. Spatially explicit models by incorporating spatial contexts by Yan et al. 2018 can outperform traditional non-spatial machine learning models in many tasks such as image classification, geographic knowledge graph summarization by Yan et al. 2019, and geographic question-answering problems (see Mai et al. 2019). Furthermore, some recently developed machine learning and particularly deep learning methods are also motivated by GIS and geography such as deep compositional spatial models by Zammit-Mangion et al. 2019, spatially conditioned generative adversarial nets (SpaceGAN) by Klemmer et al. 2019, a GeoGAN with reconstruction and style losses by Ganguli et al. 2019, and a LSTM-TrajGAN for trajectory privacy Protection by Rao et al. 2020.


It proposes a set of ten core concepts of spatial information including location, neighbourhood, field, object, network, event, granularity, accuracy, meaning, and value. These concepts can be used across multiple disciplines for enabling spatial analysis and spatial model development.


A thorough discussion about the laws in geography. After the First Law (spatial dependence) and the Second Law (spatial heterogeneity) in geography, this paper presents a new thinking about spatial prediction based on the Third Law of geography that focuses on the similarity of geographic configuration of locations. The discussion offers insights into future development of GeoAI models.


It demonstrates how utilizing the rich information embedded in spatial contexts can substantially improve the classification of place types from images and outperform state-of-the-art deep learning models such as CNN and ResNet.


It proposes a novel graph summarization method by incorporating spatially explicit components into a reinforcement learning framework for geographic knowledge graphs interlinking large-scale places, actors, events, and objects.


It reviews the uniqueness of geographic question-answering problems and presents a spatially explicit translational knowledge graph embedding model called TransGeo, which is further applied to relax and rewrite unanswerable geographic questions.


Through simulation studies the proposed deep compositional spatial models show strong capacity to model nonstationary and anisotropic spatial data.

It introduces a generative model for geospatial domains SpaceGAN that learns neighbourhood structures and enriches spatial representation of each data point rather than mere spatial coordinates. Using synthetic and real-world prediction tasks, the research suggests that SpaceGAN can be used as a tool for artificially inflating sparse geospatial data and improving generalization of geospatial models.


It develops a GeoGAN with new pixel-wise reconstruction loss and style loss design to create stylish maps from satellite images.


It proposes a novel deep learning framework LSTM-TrajGAN to generate privacy-preserving synthetic trajectory data for data sharing and publication. A spatially explicit loss metric function TrajLoss is introduced to measure the trajectory similarity for model training and optimization.

Spatial Representation Learning

The success of many machine learning algorithms generally depends on the quality of data representation or feature engineering (see Bengio et al. 2013). Thus, latent feature learning or representation learning for spatially explicit AI techniques by considering spatial constraints and relationships have attracted much attention in GeoAI (see Janowicz et al. 2020). Researchers have utilized representation learning for latent geospatial feature representation, such as Place2Vec for place types, built environment, and region representation by Yan et al. 2017; Zhang et al. 2017; Liu et al. 2019; Zhai et al. 2019, Road2Vec embedding for road segments and traffic prediction by Deng et al. 2016; Liu et al. 2017, Mot2Vec embedding for mobility and visit traces by Crivellari and Beinat 2019, Tile2Vec embedding for remote sensing data by Jean et al. 2019, and multi-scale location encoding Space2Vec for spatial feature distributions by Mai et al. 2020.


It reviews key concepts and progress in the area of unsupervised feature learning and deep learning.

It also outlines new perspectives for learning good data representations, computing representations
(i.e., inference), and the connections between representation learning, density estimation, and manifold learning (an approach to nonlinear dimensionality reduction).


A novel method to augment the spatial contexts of POI types using a distance-binned, information-theoretic approach is proposed to generate place-type embeddings. It outperforms non-spatial Word2Vec and other representation models using three different machine and human intelligence evaluation tasks and strongly correlates with human assessments of POI type similarity.


A new cross-modal representation learning method for uncovering urban dynamics with massive geotagged social media data is developed. It jointly embeds all spatial, temporal, and textual dimensions into data representations.


It proposes a representation learning model using spatial contexts to explore place niche patterns and demonstrates potential for information retrieval and place recommendation tasks.


It combines Place2Vec representation learning of POIs and clustering approaches for urban functional region identification and neighborhood classification.


A latent space modeling framework for road networks (LSM-RN) is proposed for more accurate and scalable traffic prediction by utilizing both topology similarity and temporal correlations.
The proposed Road2Vec can quantify the implicit spatial interactions among road segments based on real-world vehicle operating data. Such embedding techniques capturing underlying heterogeneous and non-linear traffic properties can be used for more accurate short-term traffic forecasting along road networks.

Mot2Vec is proposed to derive multidimensional vector representations of locations, traces and visitors through an unsupervised machine learning approach, which enables direct comparison of locations’ connectivity, provides analogous similarity distributions for places of the same type, and identifies common human movement behaviors.

It proposes an unsupervised representation learning algorithm Tile2Vec that extends the distributional context hypothesis from natural language to spatially distributed data such as remote sensing images.

A novel representation learning model called Space2Vec is proposed to encode the absolute positions and spatial relationships of places. Experiment results show that such a multiscale spatial representation model outperforms traditional models in POI type prediction and image classification tasks.

Spatial Prediction and Interpolation
The basic idea of spatial prediction is to estimate the values of a geographic variable at unknown locations using known location values or multivariate data analysis (see more details in Zhu et al. 2018). Spatial interpolation is one type of spatial prediction functionality in GIS. Traditional methods of spatial interpolation include Inverse Distance Weighting (IDW) and Triangulated Irregular Networks (TIN), etc. Innovative use of machine learning and deep learning in spatial prediction includes, for example, new
development of spatial interpolation methods using conditional generative adversarial neural networks by Zhu et al. 2020a, interpolation and prediction of activity locations from sparsely sampled mobile phone location data by Li et al. 2019 and Li et al. 2020, classification of GPS noise levels using convolutional neural networks (CNN) for accurate distance estimation by Murphy et al. 2017, traffic sign recognition for traffic rule updating by Xing et al. 2019, and enhancing trip distribution prediction by Pourebrahim et al. 2018. In addition, many human activities happen along road networks. Thus, spatiotemporal prediction of traffic flows, urban mobility patterns, and crimes also attracts large attention (more information in Zhang et al. 2019; Zhao et al. 2019; Ren et al. 2020; Zhang and Cheng 2020).


A novel deep learning architecture named conditional encoder-decoder generative adversarial neural networks (CEDGANs) is proposed for spatial interpolation tasks. A case study on digital elevation models (DEM) shows that the CEDGANs outperform benchmark spatial interpolation methods in both accuracy and visual fidelity because it can capture local geographical structure patterns.


A machine learning-based multi-criteria data partitioning trajectory reconstruction method (MDP-TR) is proposed to interpolate and reconstruct human movement trajectories from large-scale low-frequently sampled mobile phone location data. One key concept for designing this intelligent method is considering the similarity among multiple trajectories and the temporal patterns of missing location data.


A novel trajectory prediction method called the trajectory predictor with fuzzy-long short-term memory network (TrjPre-FLSTM) is introduced by overcoming the sharp boundary limitation and considering period movement patterns of individual trajectories.


A CNN approach to classifying the noise level of the input ride-sharing GPS data on any given route is proposed to reduce the distance errors between the predicted and ground-truth traces of actual ride data and to find the best estimate of the driving path.

A deep learning-based traffic sign recognition system for traffic rule updating (such as no left/right/U-turn, no parking, and speed limit) is developed by DiDi Chuxing. The object detection and classification based on deep neural networks and a model compression method are deployed on their driving vehicle recorders.


It compares the performance of artificial neural networks and the gravity model in predicting the home-work commuting flows between census tracts of the New York City. The models use population, employment, distance, and number of geotagged-tweets in the origin-destination zones as variables. It shows that adding the social media information may improve the model performance in trip distribution prediction.


A deep convolutional neural network (DCNN) is developed to identify high-level scene features from street view images that can explain up to 66.5% of the hourly variation of taxi trips along urban road networks. It presents a smart approach to bridge the gaps between the physical sensing and human activity sensing.


A novel temporal graph convolutional network T-GCN is proposed for traffic prediction, which uses the GCN to learn complex topological structures for capturing spatial dependence and uses the gated recurrent unit to learn dynamic changes of traffic data for capturing temporal dependence.

It introduces a long short-term memory neural network into the ST-ResNet to form a hybrid integrated deep learning model to predict urban traffic flows.


It proposes a gated localized diffusion neural network (GLDNet) for predictive hotspots of sparse spatio-temporal events along road networks. A case study using crime data in the Chicago is conducted to validate the effectiveness of the GLDNet model.

**AI in Cartography and Mapping**

Recent research demonstrates great potential for implementing AI techniques especially deep learning for cartographic design and map style transferring (see recent works of Xu and Zhao 2018; Kang et al. 2019a; Huang et al. 2019), detection and extraction of map features, symbols and texts by Li and Hsu 2020; Duan et al. 2018, 2020; Xie et al. 2020; Yan et al. 2020, and cartographic generalization by Touya et al. 2019; Feng et al. 2019. These directions for the use of AI in cartography are outlined as follows. First, the use of generative adversarial networks (GAN) can be extended to other mapping contexts such as helping cartographers deconstruct the most salient stylistic elements that constitute the unique look and feel of existing designs and using this information to improve cartographic designs. Second, the topology of geographic features needs to be well retained and the map symbols and texts may require separate pattern recognition models from styling to get better outcomes. Finally, integration of AI with cartographic design may fully or partially automate the map generalization process.


The CycleGAN model is employed to transfer remote sensing image styles and geographic features of different cities from one place to another, which also shows the capability of GAN in extracting feature patterns from their spatial distribution structures in cities.


A novel framework using AI for map style transfer applicable across multiple map scales is proposed. The research identifies and transfers styles from a target group of visual examples, including Google Maps, OpenStreetMap, and artistic paintings, to unstyled GIS vector data using two conditional GAN models (Pix2Pix and CycleGAN).

The Pix2Pix GAN is employed to translate multispectral imagery derived from Landsat 8 into nighttime images with the style of the Visible Infrared Imaging Radiometer Suite (VIIRS) product.


A new deep convolutional neural network (DCNN) approach is introduced to automatically detect and extract terrain features from 12,000 remotely sensed images (1,000 original images and 11,000 derived images from data augmentation).


The research compared the performance of two DCNN models for extracting geographic features from scanned historical maps. The context module that does not use pooling layers can maintains the spatial resolution of the input historical maps (images) and thus generate fewer false positives than the fully convolutional networks (FCNs).


The research introduces a novel reinforcement learning approach to annotate precise locations of geographic features on historical scanned maps. The proposed automatic vector-to-raster alignment algorithm enables efficient searches for matching features without pre-processing steps, such as extracting specific feature signatures (e.g. road intersections) in aligning various features (roads, water lines, and railroads) with high accuracy.


A novel LOcally-COnstrained (LOCO) You-Only-Look-Once deep learning framework by incorporating spatial characteristics is proposed to detect small and densely-distributed building footprints from satellite images.

A graph convolutional autoencoder (GCAE) model consisting of the graph convolution and unsupervised auto-encoder learning architecture is proposed to classify building shapes such as E-shape, T-shape, and U-shape, and support shape matching and retrieval in digital maps.


The authors discuss key issues in use of machine learning and deep learning models in automatic map generalization process. Data enrichment and automatic evaluation of the model outputs are two key steps.


The research employs DCNN and GAN for cartographic generalizations (with a focus on building generalization in digital maps). The performance of three network architectures: U-net, residual U-net and GAN for building generalization in multiple map scales is compared using OpenStreetMap. The residual U-net is found to outperform the other two models in the building generalization experiments.

**Deep Learning in Earth Observation**

Recent advancement in deep learning has revolutionized multiple domains in both scientific and practical ways (see LeCun et al. 2015). Researchers find that the integration of spatiotemporal features extracted from remote sensing big data with deep learning models offers capabilities for better understanding of data-driven and physical process-based Earth system science (as described by Reichstein et al. 2019; Zhu et al. 2017), including various Earth observation applications such as land cover and land use classification by Scott et al. 2017; Huang et al. 2018, air quality monitoring by Li et al. 2017, soil mapping by Behrens et al. 2018, environmental parameter retrieval by Yuan et al. 2020, flood mapping for natural disaster response by Peng et al. 2019, and transportation infrastructure extraction by Tao et al. 2019.


This perspective paper summarizes state-of-the-art machine learning approaches to geoscientific tasks, such as weather forecasts, land-use change detection, atmospheric flux prediction, and physical transport modeling. It identifies five major challenges for the successful adoption of deep learning approaches in the geosciences, including interpretability, physical consistency, complex and
uncertain data, limited labels, and computational demand. It calls for a hybrid modeling approach with coupling physical process models with data-driven machine learning.


It analyzes the challenges and unique questions of using deep learning for remote-sensing data analysis (such as multi-modal, geo-located, measurements with controlled uncertainty, geo-physical and bio-chemical quantities), reviews state-of-the-art deep learning models for remote sensing data analysis, and provides resources including data sources, tutorials and open-source deep learning frameworks to advance this field.


To overcome the limited label issue in deep-learning based land cover classification using remote sensing image data, the research employs two techniques in conjunction with DCNN: transfer learning with fine-tuning technique and data augmentation technique tailored specifically for improving network training of remote sensing imagery. Three different DCNNs derived from CaffeNet, GoogLeNet, and ResNet50 all show high land-cover classification accuracies on two different remote sensing data sets.


A semi-transfer deep convolutional neural network (STDCNN) approach is proposed to overcome some limitations when applying traditional DCNN methods in remote sensing such as no more than three multispectral channels, limited training samples and uniform decomposition of large images. The proposed STDCNN model is used to generate high accuracy urban land-use maps from WorldView-2 and WorldView-3 high spatial resolution (HSR) remote sensing images.


A novel joint deep learning framework that incorporates patch-based CNN and pixel-based multilayer perceptron with joint reinforcement and mutual complementarity is proposed for land cover and land use (LCLU) classification simultaneously. The proposed approach is tested on aerial photography of
two large urban and suburban areas in Great Britain (Southampton and Manchester) and shows a
good performance in automating joint LCLU classification tasks together.

satellite and station observations: a geo-intelligent deep learning approach. Geophysical Research
Letters, 44(23), 11-985.

A GeoAI approach that incorporates geographical correlation into a deep belief network learning
architecture is proposed to estimate the spatial distribution of ground level PM2.5 concentration by
fusing satellite and station observation data. Experiments in China show that the proposed Geoi-DBN
model outperforms other traditional non-spatial neural networks.

with deep learning. Scientific reports, 8(1), 1-9.

The research introduces a mixed-scaling method with deep learning for digital soil mapping that
overcomes some issues (such as neighbor size and decomposition artefact) when using traditional
terrain feature construction methods and preserves the landscape features across multiple scales.

Yuan, Q., Shen, H., Li, T., Li, Z., Li, S., Jiang, Y., ... and Zhang, L. (2020). Deep learning in environmental

It provides a comprehensive review on deep learning approaches to environmental remote sensing. It
summarizes key deep neural network architectures and achievements in various environmental fields
including land cover, vegetation parameters, agricultural yield prediction, land surface and air
temperature, aerosol, particulate matter, precipitation, soil moisture, snow cover, evapotranspiration,
radiation, and ocean color parameters. It discusses different ways of integration of physical models,
spatiotemporal characteristics with deep learning.

2492.

The research develops a new patch similarity convolutional neural network (PSNet) using satellite
multispectral surface reflectance imagery instead of raw pixel digital numbers before and after
flooding with a 3-meter spatial resolution, which can mitigate the influence of inconsistent illumination
caused by varied weather conditions at different times of data collection. Experiments on two
hurricane-related flooding events show high accuracy and recall of the proposed model.

A spatial information inference structure that enables multidirectional message passing between pixels is integrated to a deep learning-based semantic segmentation framework for road information extraction from very high-resolution (VHR) satellite imagery. It shows the importance of preserving different levels (the global-level, local-level and object-level) of contextual information in semantic segmentation to keep the continuity of the extracted road networks.

**GeoAI in Social Sensing**

Compared to remote sensing data that have been successfully used to extract physical characteristics of the Earth surface, social sensing data complement remote sensing data by revealing human dynamics and the underlying socioeconomic characteristics using various data sources (e.g., mobile phone data, taxi GPS trajectories, location-based social networks, and social media) (see the definition of social sensing by Liu et al. 2015). The process of social sensing involves the creation of multi-dimensional semantic data signatures (i.e., spatial, temporal, and thematic features defined by Janowicz et al. 2019.) from location-based digital traces. Much of social sensing research is rooted in the concept of place, including understanding place characteristics in geographic contexts by Zhu et al. 2020b, and extraction of human emotions at different places from facial expressions by Kang et al. 2019b, etc. With the advancement of drive-by sensors, computer vision and deep learning techniques, street-level images become a new data source for understanding the physical environments and social environments, such as estimating the demographic makeup of neighborhoods by Gebru et al. 2017, understanding human perception of places using semantically segmented scene elements by Zhang et al. 2018, examining association of street green and blue spaces with geriatric depression by Helbich et al. 2019. Furthermore, the emergence of various types of geospatial big data provides new opportunities for social sensing. Multiple geospatial data fusion with deep learning is a new research theme, such as fusion of remote sensing and social sensing data for urban functional region recognition by Cao et al. 2020, fusion of street view images and social media check-ins for uncovering inconspicuous places by Zhang et al. 2020, and combination of street view images and OpenStreetMap data for street frontage classification by Law et al. 2020.


One of the pioneer social sensing papers that focus on theoretical contributions. It introduces key concepts, compares the major sources, signals and processing methods of social sensing with remote sensing, and points out major issues when applying social sensing analytics. It also suggests
that social sensing data contain rich information about spatial interactions and place semantics. But we need to pay more attention to representativeness and data quality issues.

Janowicz, K., McKenzie, G., Hu, Y., Zhu, R., and Gao, S. (2019). Using semantic signatures for social sensing in urban environments. In Mobility patterns, big data and transport analytics (pp. 31-54). Elsevier. It systematically summarizes the social sensing methodological framework of semantic signatures that include spatial, temporal, and thematic features constructed from digital traces of human-place interactions. Six social sensing applications are introduced for studying urban environments using semantic signatures, including comparing place types, gazetteers matching, geoprivacy, temporally enhanced geolocation service, regional variation analysis, and extraction of urban functional regions.

Zhu, D., Zhang, F., Wang, S., Wang, Y., Cheng, X., Huang, Z., and Liu, Y. (2020b). Understanding place characteristics in geographic contexts through graph convolutional neural networks. Annals of the American Association of Geographers, 110(2), 408-420. It employs graph convolutional neural networks (GCNs) to model spatial interactions among places as a graph, where each place is formalized as a node, place characteristics are encoded as node features, and place connections are represented as the edges. It also discusses the influence of different place connection measures (self-only connection, adjacency, and spatial interactions) on the prediction accuracy for unobserved region characteristics using over 240,000 POIs in Beijing.

Kang, Y., Jia, Q., Gao, S., Zeng, X., Wang, Y., Angsuesser, S., Liu, Y., Ye, X., and Fei, T. (2019b). Extracting human emotions at different places based on facial expressions and spatial clustering analysis. Transactions in GIS, 23(3), 450-480. It introduces the concept of place emotion, which is a special category of the human affective computing at different places. Then, it presents a methodological framework of extracting human emotions from facial expressions in photos using state-of-the-art computer vision and deep learning techniques and attaching to places using a spatial clustering technique. Much of the emotional variation at different places can be explained by a few geographic and environmental factors.


Over 110,000 street view images captured spanning 56 cities in 28 countries are trained using DCNN to extract six dimensions of human perceptions on urban environments including safe, lively, beautiful, wealthy, depressing, and boring. This learning framework is then applied to infer the spatial distribution of city-wide human perceptions in new cities. A set of objects from image segmentation results are identified to link the perceptual indicators.


A fully CNN for semantic segmentation (i.e., the FCN-8s) is applied to extract streetscape green and blue spaces from street view images and satellite-based remote sensing images. The mental health of elderly people is found to be enhanced by exposure to green and blue spaces in street views but no significant evidence is found to associate with remote sensing-based metrics.


A novel end-to-end deep learning-based remote and social sensing data fusion model is developed to automatically extract urban functional regions. Residual neural network (ResNet), spatial pyramid pooling (SPP-Net), and stacked bidirectional long short-term memory network (LSTM-Net) are employed to learn multi-dimensional social sensing and remote sensing features. Three different fusion methods for combining multi-modal features are compared: concatenation, element-wise sum, and element-wise max pooling.


A novel framework of extracting place-based multi-dimensional features is proposed to characterize places regarding place type, human activity, visit group, and locale environment using multi-source big geo-data. Individual-level social media check-in data are effective for differentiating locals and visitors. High-level features extracted from street view images using deep learning are useful to describe the surrounding streetscape of places. Such a data-synthesis-driven framework can facilitate place-based knowledge discovery and policy making.

A deep learning model Street-Frontage-Net is developed to help evaluate the quality of street frontage as either being active (frontage containing windows and doors) or blank (frontage containing walls, fences and garages). Multiple features can be extracted from street view images and street network morphology images, which provides new insights for urban planning and management to identify active frontages in different neighborhoods.

Geospatial Semantics and Geo-Text Analysis
Digital Gazetteers are dictionaries of geo-referenced places and geo-text data analysis play an important role in geographic information retrieval (GIR), spatial-temporal knowledge organization and data-driven semantics research (see Janowicz et al. 2012; Hu 2018). Most of the gazetteer databases are maintained by authoritative agencies. It is time consuming to update place entries because of high costs. Extraction and integration techniques to automatically obtain geographic information from spatiotemporal linked data and volunteered geographic information sources have recently come to the spotlight (see Janowicz et al. 2012; Gao et al. 2017). Key processing steps in geo-text data analysis include place name disambiguation, toponym matching, footprint extraction, etc. Topic modeling, rule-based matching, machine learning and deep learning approaches have been proposed for the geo-text data processing by Ju et al. 2016; Santos et al. 2018; Acheson et al. 2020; Wang et al. 2020. Intelligent applications of geospatial semantics contain understanding place environments and human sentiments from user textual reviews by Hu et al. 2019c, translation of natural language queries to GIS functionality and operation tools by Scheider et al. 2019. In addition, there are increasingly use of social media text data with deep learning approaches to extract situational awareness information at different place resolutions during natural disasters by Yu et al. 2019; Wang et al. 2020.


It outlines the research field of geospatial semantics including two major directions: semantic modeling and semantics-based search, integration, and interoperability of geo-referenced information. Then, key progress and challenges in geospatial semantics research fields are summarized, including geo-ontology engineering, semantic reference systems, semantic primitives and information grounding, event discovery and spatiotemporal ontologies, places and semantic trajectories, sensor and observation semantics, and spatial data infrastructures.

A novel approach to improving place name disambiguation from short texts by combining entity co-occurrence on Linked Data with topic modeling is proposed and is found to outperform benchmark systems such as DBpedia Spotlight and Open Calais in place name disambiguation tasks.


A high-performance Hadoop-based geoprocessing platform with a data-driven approach to constructing digital gazetteers (dictionary of place names with footprints) from volunteered geographic information is introduced. It demonstrates how to use spatial-function enabled cloud computing infrastructure to facilitate geospatial semantics research.


It introduces the key concepts and types of geo-text data in GIS and reviews several applications of geospatial semantics including extracting place names, place-based relations, sentiment/emotions, zones, and impacts. A generalized workflow utilizing natural language processing and spatial clustering for analyzing geo-text data is proposed, including data retrieval, geoparsing, data analysis, evaluation, and result visualization.


A novel deep neural network is proposed to classify 5 million pairs of toponyms in the GeoNames gazetteer as either matching or non-matching. The performance of the proposed method is better than other traditional supervised machine learning approaches for multiple string similarity metrics.


The research utilizes natural language processing techniques to extract semantic topics and human sentiments that people express towards their neighborhoods. An experiment using online textual reviews about the neighborhoods in New York City is conducted and the results can be used for supporting urban planning and studies of living environments.
This research examines the capability of a deep learning model in cross-event social media textual topic classification for disaster situational awareness based on three geo-tagged Twitter datasets collected during Hurricanes Sandy, Harvey, and Irma. The experiment results demonstrate that CNN models achieve a consistently better accuracy for both single event and cross-event evaluation scenarios than the SVM and logistic regression models.

The research systematically investigates a variety of analytic questions linking to common GIS tools and proposes a semantic web framework to intelligently match analytic questions to spatial analysis tools that are capable of answering those questions. Examples for the translation of GIS operations to SPARQL queries are demonstrated.

This research compares the use of machine learning approach (i.e., random forests) and rule-based approach to cross-gazetteer matching of natural features in two gazetteers, GeoNames and SwissNames3D. The random forests model performs better gain than the rule-based approach regarding matching feature types, but only achieves negligible gains from specialized matching features. Open-source data and tools used in this research are shared on Github to support replicable and reproducible research.

A bidirectional RNN-based toponym recognition model (NeuroTPR) is proposed to address the linguistic irregularity issues associated with social media text data, such as informal sentence structures, inconsistent letter cases, name abbreviations, and misspellings. An automatic workflow for generating annotated data sets from Wikipedia articles is developed for training toponym recognition models. The NeuroTPR model performs better than other baseline toponym recognition models in a Twitter data set from Hurricane Harvey.