

5 结 论

本文详细调研了国内外轨迹路网匹配技术,包括全局算法和局部算法.很多算法只适合于高采样率的轨迹,不适合于低采样率的轨迹,而基于隐马尔可夫的算法成为主流,因此,本文详细综述了基于隐马尔可夫模型的路网匹配算法,分析了各种不同算法的优势和不足,最后给出了研究挑战和趋势.

References:

- [1] Li X, Han J, Lee J, Gonzalez H. Traffic densitybased discovery of hot routes in road networks. In: Proc. of the 10th Int'l Symp. on Spatial and Temporal Databases, Vol.4605. 2007. 441–459. [doi: 10.1007/978-3-540-73540-3_25]
- [2] Yuan YF, Van LH, Van WF, Hoogendoorn S. Network-Wide traffic state estimation using loop detector and floating car data. *Journal of Intelligent Transportation Systems*, 2014,18(1):41–50. [doi: 10.1080/15472450.2013.773225]
- [3] Yuan NJ, Zheng Y, Xie X, Wang YZ, Zheng K, Xiong H. Discovering urban functional zones using latent activity trajectories. *IEEE Trans. on Knowledge and Data*, 2015,27(3):712–725. [doi: 10.1109/TKDE.2014.2345405]
- [4] Zheng, Y, Wang L, Xie X, Ma W. GeoLife: Managing and understanding your past life over maps. In: Proc. of the 9th Int'l Conf. on Mobile Data Management. 2008. 211–212. [doi: 10.1109/MDM.2008.20]
- [5] Pfozer D, Jensen CS. Capturing the uncertainty of moving-object representations. *Lecture Notes in Computer Science*, 1999,1651: 111–131. [doi: 10.1007/3-54 0-48482-5_9]
- [6] Joshi RR. A new approach to map matching for in-vehicle navigation systems: The rotational variation metric. In: Proc. of the ITS. 2001. 33–38. [doi: 10.1109/ITSC.2001.948625]
- [7] Feijoo C, Ramos J, Perez F. A system for fleet management using differential GPS and VHF data transmission mobile networks. In: Proc. of the VNIS. 1993. 445–448. [doi: 10.1109/VNIS.1993.585667]
- [8] Chen M, Liu Y, Yu X. Predicting next locations with object clustering and trajectory clustering. In: Proc. of the PAKDD. 2015. 344–356. [doi: 10.1007/978-3-319-18032-8_27]
- [9] Alvarez-Garcia JA, Ortega JA, Gonzalez-Abril L, Velasco F. Trip destination prediction based on past GPS log using a hidden Markov model. *Expert Systems with Applications*, 2010,37(12):8166–8171. [doi: 10.1016/j.eswa.2010.05.070]
- [10] Mori U, Mendiburu A, Álvarez M, Lozano JA. A review of travel time estimation and forecasting for advanced traveler information systems. *Transportmetrica A: Transport Science*, 2015,11(2):119–157. [doi: 10.1080/23249935.2014.932469]
- [11] Krumm J. A Markov model for driver turn prediction. *SAE World Congress*, 2008,22(1):1–25.
- [12] Kuehne RRP, Schiifert J, Mikat KV, Tbiessenbusent V, Lorkowski BS. New approaches for traffic management in metropolitan areas. In: Proc. of the 10th IFAC Symp. on Control in Transportation Systems. 2003. 209–214.
- [13] Lü L, Chen M, Liu Y, Yu XH. A plane moving average algorithm for short-term traffic flow prediction. In: Proc. of the Advances in Knowledge Discovery and Data Mining. 2015. 357–369.
- [14] Pang LX, Chawla S, Liu W, Zheng Y. On detection of emerging anomalous traffic patterns using GPS data. *Data and Knowledge Engineering*, 2013,87(9):357–373. [doi: 10.1016/j.datak.2013.05.002]
- [15] Long X, Jin L, Joshi J. Exploring trajectory-driven local geographic topics in foursquare. In: Proc. of the Int'l Workshop on Location-based Social Networks. 2012. 927–934. [doi: 10.1145/2370216.2370423]
- [16] Yuan Q, Cong G, Ma Z, Sun A, Magnenat-Thalmann N. Who, where, when and what: Discover spatio-temporal topics for Twitter users. In: Proc. of the SIGKDD. 2013. 605–613. [doi: 10.1145/2487575.2487576]
- [17] Gonzalez H, Han J, Li X, Myslinska M, Sondag JP. Adaptive fastest path computation on a road network: A traffic mining approach. In: Proc. of the VLDB. 2007. 794–805.
- [18] Wei LY, Zheng Y, Peng WC. Constructing popular routes from uncertain trajectories. In: Proc. of the SIGKDD. 2012. 195–203.
- [19] Yuan J, Zheng Y, Xie X, Sun GZ. T-Drive: Enhancing driving directions with taxi drivers' intelligence. *IEEE Trans. on Knowledge and Data Engineering*, 2013,26(1):220–232. [doi: 10.1109/TKDE.2011.200]
- [20] Patterson DJ, Liao L, Fox D, Kautzy H. Inferring high-level behavior from low-level sensors. In: Proc. of the UbiComp. Springer-Verlag, 2003. 73–89. [doi: 10.1007/978-3- 540-39653-6_6]

- [21] Rauschert I, Agrawal P, Sharma R, Fuhrmann S, Brewer I, MacEachren A, Wang HM, Cai G. Designing a human-centered, multimodal GIS interface to support emergency management. In: Proc. of the Int'l Symp. on Advances in Geographic Information Systems. 2003. 119–124. [doi: 10.1145/585147.585172]
- [22] Li M, Zhang Y, Wang W. Analysis of congestion points based on probe car data. In: Proc. of the ITS. 2009. 1–5. [doi: 10.1109/ITSC.2009.5309869]
- [23] Mohammed AQ, Robert BN, Washington YO. A high accuracy fuzzy logic based map matching algorithm for road transport. *Journal of Intelligent Transportation Systems*, 2006,10(3):103–115. [doi: 10.1080/15472450600793560]
- [24] Yuan NJ, Zheng Y, Xie X, Wang YZ, Zheng K, Xiong H. Discovering urban functional zones using latent activity trajectories. *IEEE Trans. on Knowledge and Data Engineering*, 2015,27(3):712–725. [doi: 10.1109/TKDE.2014.2345405]
- [25] Shang J, Zheng Y, Tong W, Chang E, Yu Y. Inferring GAS consumption and pollution emission of vehicles throughout a city. In: Proc. of the SIGKDD. 2014. 1027–1036. [doi: 10.1145/2623330.2623653]
- [26] Bernstein D, Kornhauser A. An introduction to map matching for personal navigation assistants. *Geometric Distributions*, 1996, 122(7):1082–1083.
- [27] White CE, Bemstein D, Komhauser AL. Some map matching algorithms for personal navigation assistants. *Transportation Research Part C: Emerging Technologies*, 2000,8(1):91–108. [doi: 10.1016/S0968-090X(00)00026-7]
- [28] Taylor G, Blewitt G, Steup D, Corbett S, Car A. Road reduction filtering for GPS-GIS navigation. *Trans. in GIS*, 2001,5(3): 193–207. [doi: 10.1111/1467-9671.00077]
- [29] Alt H, Efrat A, Rote G, Wenk C. Matching planar maps. *Journal of Algorithms*, 2003,49(2):262–283. [doi: 10.1016/S0196-6774(03)00085-3]
- [30] Quddus MA, Ochieng WY, Zhao L, Noland RB. A general map matching algorithm for transport telematics applications. *GPS Solutions*, 2003,7(3):157–167. [doi: 10.1007/s10291-003-0069-z]
- [31] Abbour M, Bonnifait P, Cherfaoui V. Map matching integrity using multi-sensor fusion and multi-hypothesis road tracking. *Journal of Intelligent Transportation Systems Technology Planning and Operations*, 2008,6(4):189–201.
- [32] Nadine S, Kay WA. Map matching of GPS traces on high-resolution navigation networks using the multiple hypothesis technique (MHT). *Working Paper Transport and Spatial Planning*, 2009,(10):568–588.
- [33] Ochieng WY, Quddus M, Noland RB. Map-Matching in complex urban road networks. *Revista Brasileira De Cartografia*, 2003, 55(2):1–14.
- [34] Quddus MA, Noland RB, Ochieng WY. Validation of map matching algorithm using high precision positioning with GPS. *Journal of Navigation*, 2004,58(2):257–271. [doi: 10.1017/S0373463305003231]
- [35] Kim S, Kim J. Adaptive fuzzy-network based C-measure map-matching algorithm for car navigation system. *IEEE Trans. on Industrial Electronics*, 2001,48(2):432–440. [doi: 10.1109/41.915423]
- [36] Syed S, Cannon ME. Fuzzy logic-based map-matching algorithm for vehicle navigation system in urban canyons. In: Proc. of the Ion National Technical Meeting. 2004. 982–993.
- [37] Su H, Chen J, Xu J. A adaptive map matching algorithm based on fuzzy-neural-network for vehicle navigation system. In: Proc. of the WCICA. 2008. 4448–4452. [doi: 10.1109/WCICA.2008.4593639]
- [38] Haibin S, Jiansheng T, Chaozhen H. A integrated map matching algorithm based on fuzzy theory for vehicle navigation system. In: Proc. of the ICCIAS. 2006. 916–919. [doi: 10.1109/ICCIAS.2006.294272]
- [39] Zhang L, Liu JW, Wang RC, Wang HY. Trust evaluation model based on improved D-S evidence theory. *Journal on Communications*, 2013,34(7):167–173 (in Chinese with English abstract).
- [40] El Najjar ME, Bonnifait P. A road-matching method for precise vehicle localization using belief theory and kalman filtering. *Autonomous Robots*, 2005,19(2):173–191. [doi: 10.1007/s10514-005-0609-1]
- [41] Nassreddine G, Abdallah F, Denoeux T. Map matching algorithm using belief function theory. In: Proc. of the IF. 2008. 1–8.
- [42] Yang D, Cai B, Yuan Y. An improved map-matching algorithm used in vehicle navigation system. *Intelligent Transportation Systems*, 2003,11(2):1246–1250. [doi: 10.1109/ITSC.2003.1252683]
- [43] Obradovic D, Lenz H, Schupfner M. Fusion of map and sensor data in a modern car navigation system. *Journal of Signal Processing Systems*, 2006,45(1):111–122. [doi: 10.1007/s11265-006-9775-4]

- [44] Xu H, Liu HC, Tan CW, Bao Y. Development and application of an enhanced kalman filter and global positioning system error-correction approach for improved map matching. *Journal of Intelligent Transportation Systems: Technology, Planning and Operations*, 2010,14(1):27–36. [doi: 10.1080/15472450903386013]
- [45] Kim W, Jee GI, Lee JG. Efficient use of digital road map in various positioning for ITS. In: *Proc. of the Position Location and Navigation Symp.* 2000. 170–176. [doi: 10.1109/PLANS.2000.838299]
- [46] Li Z, Chen W. A new approach to map-matching and parameter correcting for vehicle navigation system in the area of shadow of GPS signal. In: *Proc. of the ITSC, Vol.5.* 2005. 425–430. [doi: 10.1109/ITSC.2005.1520086]
- [47] Pyo JS, Shin DH, Sung TK. Development of a map matching method using the multiple hypothesis technique. In: *Proc. of the Intelligent Transportation Systems.* 2001. 23–27. [doi: 10.1109/ITSC.2001.948623]
- [48] Cherif S, El-Najjar ME, François C. A road matching method for precise vehicle localization using hybrid Bayesian network. *Intelligent Transportation Systems*, 2008,12(4):176–188. [doi: 10.1080/15472450802448153]
- [49] Yin H, Wolfson O. A weight-based map matching method in moving objects databases. In: *Proc. of the SSDBM, Vol.16.* 2004. 437–438. [doi: 10.1109/SSDM.2004.1311248]
- [50] Blazquez C, Vonderohe A. Simple map-matching algorithm applied to intelligent winter maintenance vehicle data. *Journal of the Transportation Research Board*, 2005,1935(1):68–76. [doi: 10.3141/1935-08]
- [51] Brakatsoulas S, Pfoser D, Salas R, Wenk C. On map-matching vehicle tracking data. In: *Proc. of the VLDB.* 2005. 853–864.
- [52] Honey SK, Zavoli WB, Milnes KA, Phillips AC, Jr White MS, Jr Loughmiller GE. *Vehicle navigational system and method: US.* US4796191, 1989.
- [53] Pink O, Hummel B. A statistical approach to map matching using road network geometry, topology and vehicular motion constraints. In: *Proc. of the ITS.* 2008. 862–867. [doi: 10.1109/ITSC.2008.4732697]
- [54] Bierlaire M, Chen J, Newman J. A probabilistic map matching method for smartphone GPS data. *Transportation Research Part C: Emerging Technologies*, 2013,26(1):78–98. [doi: 10.1016/j.trc.2012.08.001]
- [55] Zhang ZH, Cui TJ, Yao HM. New map matching calculation method in vehicle navigation system. *Hydrographic Surveying and Charting*, 2006,26(2):55–58 (in Chinese with English abstract).
- [56] Newson P, Krumm J. Hidden Markov map matching through noise and sparseness. In: *Proc. of the ACM-GIS.* 2009. 336–343. [doi: 10.1145/1653771.1653818]
- [57] Greenfield JS. Matching GPS observations to locations on a digital map. In: *Proc. of the TRB.* 2002. <https://trid.trb.org/Results?q=&serial=%22Transportation%20Research%20Board%2081st%20Annual%20Meeting%22>
- [58] Wenk C, Salas R, Pfoser D. Addressing the need for map-matching speed: Localizing global curve-matching algorithms. In: *Proc. of the SSDBM.* 2006. 379–388. [doi: 10.1109/SSDBM.2006.11]
- [59] Chawathe SS. Segment-Based map matching. In: *Proc. of the Intelligent Vehicles Symp.* 2007. 1190–1197. [doi: 10.1109/IVS.2007.4290280]
- [60] Lou Y, Zhang C, Zheng Y, Wang W, Huang Y. Map-Matching for low-sampling-rate GPS trajectories. In: *Proc. of the ACM-GIS.* 2009. 352–361.
- [61] Yuan J, Zheng Y, Zhang C, Xie X, Sun JZ. An interactive-voting based map matching algorithm. In: *Proc. of the MDM.* 2010. 43–52. [doi: 10.1109/MDM.2010.14]
- [62] Giovannini L. A novel map-matching procedure for low-sampling GPS data with applications to traffic flow analysis [Ph.D. Thesis]. *Universita Di Bologna*, 2011.
- [63] Zheng K, Zheng Y, Xie X, Zhou XF. Reducing uncertainty of low sampling rate trajectories. In: *Proc. of the ICDE.* 2012. 1144–1155.
- [64] Civilis A, Jensen CS, Pakalnis S. Techniques for efficient road-network based tracking of moving objects. *IEEE Trans. on Knowledge and Data Engineering*, 2005,17(5):698–712. [doi: 10.1109/TKDE.2005.80]
- [65] Thiagarajan A, Ravindranath L, Lacerus K, Madden S, Balakrishnan H, Toledo S, Eriksson J. VTrack: Accurate, energy-aware road traffic delay estimation using mobile phones. In: *Proc. of the Sensys.* 2009. 85–98.
- [66] Thiagarajan A, Ravindranath L, Balakrishnan H, Madden S, Girod L. Accurate, low-energy trajectory mapping for mobile devices. In: *Proc. of the USENIX.* 2011. 267–280.

- [67] Wang H, Wang Z, Shen G, Li F, Han S, Zhao F. WheelLoc: Enabling continuous location service on mobile phone for outdoor scenarios. In: Proc. of the INFOCOM. 2013. 2733–2741. [doi: 10.1109/INFOCOM.2013.6567082]
- [68] Guha S, Plarre K, Lissner D, Mitra S, Krishna B, Dutta P, Kumar S. AutoWitness: Locating and tracking stolen property while tolerating GPS and radio outages. In: Proc. of the TOSN. 2010. 29–42. [doi: 10.1145/1869983.1869988]
- [69] Aly H, Youssef M. semMatch: Road semantics-based accurate map matching for challenging positioning data. In: Proc. of the 23rd SIGSPATIAL Int'l Conf. on Advances in Geographic Information Systems. 2015. Article No.5. [doi: 10.1145/2820783.2820824]
- [70] Mohamed R, Aly H, Youssef M. Accurate and efficient map matching for challenging environments. In: Proc. of the SIGSPATIAL. 2014. 401–404. [doi: 10.1145/2666310.2666429]
- [71] Mohamed R, Aly H, Youssef M. Accurate real-time map matching for challenging environments. IEEE Trans. on Intelligent Transportation Systems, 2017,18(4):847–857. [doi: 10.1109/TITS.2016.2591958]
- [72] Aly H, Youssef M. Dejavu: An accurate energy-efficient outdoor localization system. In: Proc. of the ACM-GIS. 2013. 154–163. [doi: 10.1145/2525314.2525338]
- [73] Alzantot M, Youssef M. UPTIME: Ubiquitous pedestrian tracking using mobile phones. In: Proc. of the WCNC. 2012. 3204–3209. [doi: 10.1109/WCNC.2012.6214359]
- [74] Ibrahim M, Youssef M. CellSense: A probabilistic RSSI-based GSM positioning system. In: Proc. of the GLOBECOM. 2010. 1–5. [doi: 10.1109/GLOCOM.2010.5683779]
- [75] Ibrahim M, Youssef M. A hidden Markov model for localization using low-end GSM cell phones. Proc. of the ICC, 2011,47(10): 1–5. [doi: 10.1109/icc.2011.5962993]
- [76] Ibrahim M, Youssef M. CellSense: An accurate energy-efficient GSM positioning system. IEEE Trans. on Vehicular Technology, 2011,61(1):286–296. [doi: 10.1109/TVT.2011.2173771]
- [77] Aly H, Basalamah A, Youssef M. Map++: A crowd-sensing system for automatic map semantics identification. In: Proc. of the SECON. 2014. 546–554. [doi: 10.1109/SAHCN.2014.6990394]
- [78] Goh CY, Dauwels J, Mitrovic N, Asif MT, Oran A, Jaillet P. Online map-matching based on hidden Markov model for real-time traffic sensing applications. In: Proc. of the ITSC. 2012. 776–781. [doi: 10.1109/ITSC.2012.6338627]
- [79] Rohani M, Gingras D, Gruyer D. A novel approach for improved vehicular positioning using cooperative map matching and dynamic base station DGPS concept. IEEE Trans. on Intelligent Transportation Systems, 2015,17(1):1–10. [doi: 10.1109/TITS.2015.2465141]
- [80] Pereira FC, Costa H, Pereira NM. An off-line map-matching algorithm for incomplete map databases. European Transport Research Review, 2009,1(3):107–124. [doi: 10.1007/s12544-009-0013-6]
- [81] Miwa T, Kiuchi D, Yamamoto T, Morikawa T. Development of map matching algorithm for low frequency probe data. Transportation Research Part C: Emerging Technologies, 2012,22(5):132–145. [doi: 10.1016/j.trc.2012.01.005]
- [82] Raymond R, Morimura T, Osogami T, Hirose N. Map matching with hidden Markov model on sampled road network. In: Proc. of the ICPR. 2012. 2242–2245.
- [83] Baum LE. Statistical inference for probabilistic functions of finite state Markov chains. Annals of Mathematical Statistics, 1966, 37(6):1554–1563. [doi: 10.1214/aoms/1177699147]
- [84] Baum LE, Eagon JA. An inequality with applications to statistical estimation for probabilistic functions of Markov processes and to a model for ecology. Bulletin of the American Mathematical Society, 1967,73(3):360–363. [doi: 10.1090/S0002-9904-1967-11751-8]
- [85] Baum LE, Sell GR. Growth transformation for functions on manifolds. Pacific Journal of Mathematics, 1968,27(2):211–227. [doi: 10.2140/pjm.1968.27.211]
- [86] Lamb P, Thiebaut S. Avoiding explicit map-matching in vehicle location. In: Proc. of the ITS. 1999. 8–12.
- [87] Hummel B. Map matching for vehicle guidance. In: Dynamic and Mobile GIS: Investigating Changes in Space and Time. Boca Raton: Taylor & Francis, 2006.
- [88] Krumm J, Letchner J, Horvitz E. Map matching with travel time constraints. SAE Technical Paper, 2007-01-1102, 2007. [doi: 10.4271/2007-01-1102]

- [89] Gather U, Schultze V. Robust estimation of scale of an exponential distribution. *Statistica Neerlandica*, 1999,53(53): 327–341. [doi: 10.1111/1467-9574.00115]
- [90] Wang Y, Zhu Y, He Z, Yue Y, Li Q. Challenges and opportunities in exploiting large-scale GPS probe dat. HP Laboratories, Technical Report, HPL-2011-109, 2011.
- [91] Bloit J, Rodet X. Short-Time viterbi for online HMM decoding: Evaluation on a real-time phone recognition task. In: Proc. of the ICASSP. 2008. 2121–2124. [doi: 10.1109/ICASSP.2008.4518061]
- [92] Šrámek R, Brejová B, Vinař T. On-Line viterbi algorithm and its relationship to random walks. arXiv:0704.0062v1, 2007.
- [93] Song R, Lu W, Sun W, Huang W, Chen C. Quick map matching using multi-core CPUs. In: Proc. of the ACM-GIS. 2012. 605–608. [doi: 10.1145/2424321.2424428]
- [94] Wu G, Qiu YJ, Wang GR. Map matching algorithm based on hidden Markov model and genetic algorithm. *Journal of Northeastern University (Natural Science)*, 2017,38(4):472–475 (in Chinese with English abstract).
- [95] George RJ, Thambipillai S. Online map-matching of noisy and sparse location data with hidden Markov and route choice models. *IEEE Trans. on Intelligent Transportation Systems*, 2017,18(9):2423–2434. [doi: 10.1109/TITS.2017.2647967]
- [96] Essam A, Tetsuji O, Ahmed E. Real-Time large-scale map matching using mobile phone data. *ACM Trans. on Knowledge Discovery from Data*, 2017,11(4):1–38. [doi: 10.1145/3046945]
- [97] Zheng Y, Chen Y, Xie X, Ma W. GeoLife2.0: A location-based social networking service. In: Proc. of the MDM. 2009. 357–358.
- [98] Zheng Y, Liu L, Wang L, Xie X. Learning transportation mode from raw GPS data for geographic applications on the Web. In: Proc. of the WWW. 2008. 247–256.
- [99] Eriksson J, Girod L, Hull B, Newton Y, Madden S, Balakrishnan H. The pothole patrol: Using a mobile sensor network for road surface monitoring. In: Proc. of the MobiSys. 2008. 29–39. [doi: 10.1145/1378600.1378605]
- [100] Mednis A, Strazdins G, Zviedris R, Kanonirs G, Selavo L. Real time pothole detection using Android smartphones with accelerometers. In: Proc. of the DCOSS. 2011. 1–6. [doi: 10.1109/DCOSS.2011.5982206]
- [101] Mohan P, Padmanabhan VN, Ramjee R. Nericell: Rich monitoring of road and traffic conditions using mobile smartphones. In: Proc. of the SenSys. 2008. 323–336. [doi: 10.1145/1460412.1460444]

附中文参考文献:

- [39] 张琳,刘婧文,王汝传,王海艳.基于改进 D-S 证据理论的信任评估模型.通信学报,2013,34(7):167–173.
- [55] 张振辉,崔铁军,姚慧敏.车辆导航系统中地图匹配新算法.海洋测绘,2006,26(2):55–58.
- [94] 吴刚,邱煜晶,王国仁.基于隐马尔可夫模型和遗传算法的地图匹配算法.东北大学学报(自然科学版),2017,38(4):472–475.



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