Research Summary

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Prof. Höllerer's research interests lie in the area of novel user interfaces. His research group, the "Four Eyes Laboratory," conducts research in the four 'I's of Imaging, Interaction, and Innovative Interfaces. He is interested in computing that departs from conventional modes of user interaction. Within this domain, his research spans several fields of human-computer interaction and experimental systems: augmented reality, virtual reality and other immersive display and 3D user interface technologies; machine learning and (3D) computer vision; information visualization and visual analytics; wearable, mobile, and context-aware user interfaces; multimedia information systems and multi-modal interaction; finally, his group occasionally pushes the envelope in real-time computer graphics.

Over the past 20 years, the Four Eyes Laboratory's work has innovated and had significant impact in at least four major, interrelated research areas that emerged from these research efforts:

- Augmented reality user interfaces,
- Computer vision in support of eXtended Reality
- Displays and immersion
- Visual analysis and decision making

In all of these, the research group is continuing to make significant contributions and has established itself as a key player. Prof. Höllerer formed his research group at UCSB in 2002 with the goal to expand upon, and broaden, the foundational mobile AR work he helped start at Columbia University, including the world's first outdoor mobile augmented reality system ([M1], recognized in 2017 with the IEEE ISWC/Ubicomp Early Innovator Award), the first outdoor multimedia hyperlink system [M2], the establishment of collaborative indoor/outdoor mobile AR system prototypes [M3,M5], and a mobile AR user interface framework [M4].

Augmented reality user interfaces:

Right from the beginning, the Four Eyes Lab took on the challenge of applying AR technology in *unprepared environments*. Höllerer introduced the term *Anywhere Augmentation* [A1] for the concept of AR that will work in arbitrary environments with no prior preparation (no a-priori 3D scene model, no tracking equipment or markers deployed in the environment), where one person's AR usage data will improve the next person's experience in the same environment. In 2024, eight years after the release of PokemonGO, a smart-phone game that popularized mobile AR without really relying on AR functionality, this is still the promise of mobile AR. Prof. Höllerer and his group recently conducted some of the field's first formal wide-area outdoor AR user studies, such as [A6] on AR navigation aid performance in 2023 (Also: Kim et al. TVCG 2022, and Sayyad, Sra & Höllerer ISMAR 2020), demonstrating both the current capabilities and potential as well as ongoing limitations and problems of mobile AR use.

Prof. Höllerer won an NSF CAREER award, and his group's papers received Best Paper Nominations and Honorable Mentions at IEEE ISWC, IEEE VR, and ACM VRST for early work on the Anywhere Augmentation agenda, and Best Paper awards at IEEE ISMAR later for applied computer vision work. In 2007, the lab presented HandyAR [A1], a vision-based interaction technology that removed the need for cardboard fiducial markers for tangible AR, foreshadowing the more complete hand-tracking that is in use in XR headsets today.

Together with Prof. Dieter Schmalstieg from TU Graz, Prof. Höllerer published the first academically oriented textbook for the field of Augmented Reality [A4]. Despite all the progress that the field of AR has made, there are still few publications that demonstrate concrete quantitative benefits of AR use in specific application scenarios. Prof. Höllerer's work demonstrated such benefits for the case of vocabulary learning [A5], and the work with his Ph.D. student Steffen Gauglitz, (e.g. [A3]), became the basis for start-up company Caugnate, acquired by PTC, Inc. in 2015 and enabled the industry-leading Vuforia Chalk app and suite of AR remote assistance support tools.

Computer vision in support of XR:

Focusing on real-time computer vision as an active ingredient to the AR experience was a major departure from Dr. Höllerer's Ph.D. work at Columbia, which had focused on user interface prototyping relying on high-end position and orientation sensors. His UCSB group received Best Paper and Best Short Paper awards at IEEE ISMAR [V2, V3]. Going beyond the implementation of new technologies and the prototyping of novel applications, Prof. Höllerer's work contributed to the evaluation and theoretical and practical analysis of real-time computer vision algorithms, such as feature detector and descriptor algorithms for real-time tracking [V1].

The next frontier for computer vision, as employed by augmented reality, was 3D scene reconstruction and understanding. Prof. Höllerer's group made highly cited contributions in the field of structure from motion [V4, V5]. His former Ph.D. student Chris Sweeney continues his impactful work at Meta Reality Labs. Current work in 3D vision has obviously highly benefitted from Deep Learning models. Prof. Höllerer's group contributed to that research landscape among other papers by introducing one of the first Transformer-based 3D reconstruction approaches [V6]. In synergetic 2D computer vision work, the lab presented a new data augmentation strategy for training deep neural networks robust to label noise, significantly improving state-of-the-art accuracy [V7] on several important benchmarks, such as the Clothing1M Image classification challenge. His group is further working on semi- and unsupervised machine learning techniques to utilize input from AR headsets and cameras, as well as on multi-modal machine learning fusing input from different user-observing modalities (EEG, eye tracking, camera observations and 3D depth sensing) to form better machine understanding of a user's context, cognitive state, and scene semantics (e.g. ICMI 2019, 2022 Frontiers in Computational Neuroscience).

3D Displays and Immersion:

The concept of augmented reality, as introduced above, makes common use of either head-worn or "magic-lens-style" see-through tablet or hand-held displays. In addition to such displays, Prof. Höllerer's lab has been conducting research on unencumbered immersive 3D displays. His group's work on the two-sided interactive Fogscreen, which was demonstrated at 2005 SIGGRAPH Emerging Technologies led to the world's first room-scale walk-through volumetric display [I2] (Best Student Paper award at ACM VRST 2007). Another major 3D display his group was involved in building is the UCSB Allosphere (e.g. [I1]), a spherical, three-story multi-modal immersive visualization and sonification device. The Allosphere is uniquely positioned in between CAVE environments, which give fully immersive experiences to a small number of users, and full-dome planetarium style theaters, which have extremely high outreach potential but a limited sense of immersion.

An important aspect of Prof. Höllerer's work with top-of-the-line immersive instruments is the assessment of the benefits of specific immersion factors for different important application and task categories. In collaboration with Prof. Doug Bowman from Virginia Tech, Prof. Höllerer's group first established the now common practice of **XR Simulation** for running controlled user studies of AR scenarios as simulations in high-end VR (e.g. [I3,I4,I5]). Apart from shedding light on the important question of what aspects of Virtual Reality and Mixed Reality immersion have an impact on task performance in application domains such as military training, oil and gas drilling, etc., his group also evaluated and prototyped eXtended Reality interfaces that are simply not yet possible technologically (e.g. AR displays with ultra-wide field of view [I3] and negligible latency [I3,I5], or robust unencumbered selection via hand and eye). Evaluation studies in the simulator are important complements to the user studies the lab demonstrates in the field (e.g. [A5,A6]).

Visual analysis and decision making:

After reaching the rank of full Professor in 2012, Prof. Höllerer started to tackle new research problems in the area interactive visual analytics and decision support, funded by several research grants on scalable graph visualization, interactive computer network visualization and monitoring, and information network science. This, together with the visualization opportunities that the UCSB Allosphere provided, opened up a new research direction in interactive visualization (e.g. [V4]). The group made impactful contributions to the interactive analysis and visualization of large social and information networks (e.g. [DM1]), interactive hybrid recommender systems (e.g. [DM2]), and received Best Paper Awards at IEEE CogSIMA twice (Conference on Cognitive and Computational Aspects of Situation Management), at ACM UMAP (Conference on User Modeling, Adaptation and Personalization), and at ASE/IEEE SocialCom (International Conference on Social Computing).

With a lot of momentum in the fast-changing field of machine learning support for consumer and industry products, more understanding of the inner workings of the machine learning mechanisms is needed. Towards this end, Prof. Höllerer's work in the area of joint human-machine teaming, as evidenced by the already mentioned best paper awards in two different areas, user modeling (Schaffer et al. UMAP 2018), and situational awareness (Rodriguez et al., CogSIMA 2019) has been impactful. In order to understand the effects of AI recommendations on user acceptance and performance, one needs to study and understand both human cognitive constraints (e.g. [DM4]) as well as carefully design the user experience that incorporates AI elements (e.g. [DM5]]. Prof. Höllerer collaborated with cognitive psychologists and social scientists on these frontiers, and his groups work is paving the way towards more safe and effective use of AI elements in decision-support systems.

In general, Prof. Höllerer's former Ph.D. students have all embarked on highly successful careers on their own, be it in R&D at leading industry (such as at Adobe, Apple, Meta, Microsoft, Oracle, PTC, etc.), or in academia (such as Angus Forbes at Purdue, Saiph Savage at Northeastern, Charlie Roberts at WPI, Jonathan Ventura at Cal Poly, or Yi Ding at Georgia State).

Selected Publications

PDFs at `http://www.cs.ucsb.edu/~holl/selectedpubs2024.html` and
all publications at `https://www.cs.ucsb.edu/~holl/publications.html`
Number of citations in the following table as per Google Scholar, June 2024:

Augmented reality user interfaces:

ID	Publication	#citations
[A6]	Kumaran, R., Kim, Y.J., Milner, A.E., Bullock, T., Giesbrecht, B., and Höllerer, T., 2023. The Impact of Navigation Aids on Search Performance and Object Recall in Wide-Area Augmented Reality. *ACM CHI Conference on Human Factors in Computing Systems*, April 23–28, 2023, Hamburg, Germany, 17 pages.	8
[A5]	Ibrahim, A., Huynh, B., Downey, J., Höllerer, T., Chun, D., and O'Donovan, J., 2018. ARbis Pictus: A Study of Language Learning with Augmented Reality. In: *IEEE Transactions on Visualization and Computer Graphics*, 24(11), *IEEE ISMAR 2018*, Nov. 2018, pp. 2867-2874.	155
[A4]	Schmalstieg D. and Höllerer, T.: Augmented Reality: Principles and Practice. Pearson, Addison-Wesley Professional, First Edition, June 2016.	801
[A3]	Gauglitz, S., Nuernberger, B., Turk, M., and Höllerer, T., 2014. World-Stabilized Annotations and Virtual Scene Navigation for Remote Collaboration, *Proc. ACM UIST 2014 (27th Annual Symposium on User Interface Software and Technology)*, Honolulu, HI, Oct. 2014, pp. 449-459.	248

[A2]	Lee, T. and Höllerer, T., 2007. Handy AR: Markerless Inspection of Augmented Reality Objects Using Fingertip Tracking. In: *Int'l Symposium on Wearable Computers (IEEE ISWC) 2007*, Boston, MA. Oct. 11–13, 2007. **Best Paper Nominee.**	383
[A1]	Höllerer, T., Wither, J., and DiVerdi, S., 2007. „Anywhere Augmentation": Towards Mobile Augmented Reality in Unprepared Environments. In: G. Gartner, M.P. Peterson, and W. Cartwright (Eds.), *Location Based Services and TeleCartography,* Series: *Lecture Notes in Geoinformation and Cartography*, Springer Verlag, 2007, pp. 393–416.	56

Computer vision in support of XR:

ID	Publication	#citations
[V7]	Nishi, K., Ding, Y., Rich, A. and Höllerer, T., 2021. Augmentation strategies for learning with noisy labels. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition* (pp. 8022-8031).	117
[V6]	Stier, N., Rich, A., Sen, P. and Höllerer, T., 2021. VoRTX: Volumetric 3D reconstruction with transformers for voxelwise view selection and fusion. In *2021 International Conference on 3D Vision (3DV)* (pp. 320-330). IEEE.	44
[V5]	Sweeney, C., Höllerer, T., and Turk, M., 2015. Theia: A Fast and Scalable Structure-from-Motion Library, *Proceedings of the 23rd Annual ACM Conference on Multimedia*, Brisbane, Australia, October 26-30, 2015, pp. 693-696. **Winner, ACM MM Open Source Software Competition**.	96
[V4]	Sweeney, C., Sattler, T., Höllerer, T., Turk, M., and Pollefeys, M., 2015. Optimizing the Viewing Graph for Structure-from-Motion. *Proceedings of the IEEE International Conference on Computer Vision (ICCV 2015)*, Santiago, Chile, pp. 801-809.	146
[V3]	Sweeney, C., Nuernberger, B., Turk, M., and Höllerer, T., 2015. Efficient Computation of Absolute Pose for Gravity-Aware Augmented Reality, *IEEE International Symposium on Mixed and Augmented Reality (ISMAR 2015)*, Sept. 29 - Oct. 3, Fukuoka, Japan, pp. 19-24. **Best Short Paper**.	55
[V2]	Gauglitz, S., Sweeney, C., Ventura, J., Turk, M. and Höllerer, T., 2012, November. Live tracking and mapping from both general and rotation-only camera motion. In 2012 IEEE International Symposium on Mixed and Augmented Reality (ISMAR) (pp. 13-22). IEEE. **Best Paper Award.**	67
[V1]	Gauglitz, S., Höllerer, T., and Turk, M., 2012. Evaluation of Interest Point Detectors and Feature Descriptors for Visual Tracking. *International Journal of Computer Vision (IJCV)*, Volume 94, Number 3, 2011, pp. 335–360.	569

Immersion and displays

ID	Publication	#citations
[I5]	Ren, D., Goldschwendt, T., Chang, Y.S., and Höllerer, T.: Evaluating Wide-Field-of-View Augmented Reality with Mixed Reality Simulation. *IEEE Virtual Reality (VR 2016)*, March 19-23, 2016, Greenville, SC, USA, pp. 93-102.	94
[I4]	Lee, C., Rincon, G.A., Meyer, G., Höllerer, T., Bowman, D.: The Effects of Visual Realism on Search Tasks in Mixed Reality Simulation. In: *Proceedings of IEEE Virtual Reality 2013*, Orlando, FL, March 16-23, 2013.	129
[I3]	Lee, C., Bonebrake, S., Höllerer, T., and Bowman, D.: The Role of Latency in the Validity of AR Simulation. Proc. IEEE VR 2010 *(12th Int'l Conference on Virtual Reality)*, March 20–24, 2010, Waltham, MA, pp. 11–18.	80
[I2]	Lee, C., DiVerdi, S., and Höllerer, T.: An Immaterial Depth-Fused 3D Display.	30

In: *ACM Virtual Reality Software and Technology (VRST) 2007,* Irvine, CA, Nov. 5–7, 2007. **Best Student Paper.**

[I1]	Höllerer, T., Amatriain, X., and Kuchera-Morin, J.: The Allosphere: a Large-Scale Immersive Surround-View Instrument. In: *Emerging Display Technologies Workshop (EDT 2007),* co-located with *ACM SIGGRAPH*, San Diego, CA, Aug. 4, 2007.	75

Visual analysis and decision making

ID	Publication	#citations
[DM5]	Xu, C., Lien, K.-C., and Höllerer, T., 2023. Comparing Zealous and Restrained AI Recommendations in a Real-World Human-AI Collaboration Task. *ACM CHI Conference on Human Factors in Computing Systems*, April 23–28, 2023, Hamburg, Germany, pp. 1-15.	2
[DM4]	Schaffer, J., O'Donovan, J., Michaelis, J., Raglin, A., and Höllerer, T.: I Can Do Better Than Your AI: Expertise and Explanations. In: *Proceedings of the ACM International Conference on Intelligent User Interfaces*. Los Angeles, CA, March 17-20, 2019, pp. 240-251.	120
[DM3]	Ren, D., Höllerer, T., and Yuan, X.: iVisDesigner: Expressive Interactive Design of Information Visualizations, *IEEE Transactions on Visualization and Computer Graphics*, Volume 20, Issue 12, Dec. 2014, pp. 2092-2101.	128
[DM2]	Bostandjiev, S., O'Donovan, J., Höllerer, T.: TasteWeights: A Visual Interactive Hybrid Recommender System, Proceedings of the *ACM Int'l Conference on Recommender Systems (RecSys) 2012*, Dublin, Ireland, Sept. 9–13, 2012.	386
[DM1]	Gretarsson, B., O'Donovan, J., Bostandjiev, S., Höllerer, T., Asuncion, A., Newman, D., and Smyth, P.: TopicNets: Visual Analysis of Large Text Corpora with Topic Modeling. *ACM Transactions on Intelligent Systems and Technology,* 3, 2, Article 23 (February 2012), 26 pages.	232

Foundational Mobile AR Work

ID	Publication	#citations
[M5]	Höllerer, T. and Feiner, S., 2004. Mobile augmented reality. *Telegeoinformatics: Location-based computing and services*, *21*, pp.221-260.	654
[M4]	Höllerer, T., Feiner, S., Hallaway, D., Bell, B., Lanzagorta, M., Brown, D., Julier, S., Baillot, Y. and Rosenblum, L., 2001. User interface management techniques for collaborative mobile augmented reality. *Computers & Graphics*, *25*(5), pp.799-810.	218
[M3]	Höllerer, T., Feiner, S., Terauchi, T., Rashid, G. and Hallaway, D., 1999. Exploring MARS: developing indoor and outdoor user interfaces to a mobile augmented reality system. *Computers & Graphics*, *23*(6), pp.779-785.	742
[M2]	Höllerer, T., Feiner, S. and Pavlik, J., 1999, October. Situated documentaries: Embedding multimedia presentations in the real world. In *Digest of Papers. Third International Symposium on Wearable Computers* (pp. 79-86). IEEE.	348
[M1]	Feiner, S., MacIntyre, B., Höllerer, T. and Webster, A., 1997. A touring machine: Prototyping 3D mobile augmented reality systems for exploring the urban environment. *Personal Technologies*, *1*, pp.208-217.	1815