Final Report for DFG project EC437/1-1 - Decentralized Ubiquitous Computing in Everyday Environments

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FINAL REPORT

1 General Information

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2 Summary

2.1 German

Dieses Forschungsprojekt hatte zum Ziel, die negativen Folgen der Zentralisierung in unserem heutigen digitalen Ökosystem zu analysieren, und insbesondere neue Methoden und Werkzeuge zu entwickeln, um diesem Trend entgegenzusteuern. Wir haben uns besonders auf die Bereiche “Smart Home” sowie “Tangible Interaction” konzentriert, in welchen viele existierende Systeme ohne Einsatz von Cloud Services gar nicht denkbar wären. Gleichzeitig bringt dieser weit verbreitete Ansatz die Privatsphäre und informationelle Selbstbestimmung der Benutzer in Gefahr, oft sogar ohne deren explizites Wissen. Wir haben eine breite Auswahl an Interaktionsmethoden, Toolkits, und Benutzerstudien vorgestellt, die alle unter dem gemeinsamen Nenner der Dezentralisierung stehen: wie können wir zeitgemäße digitale Umgebungen schaffen, ohne uns auf zentralisierte und proprietäre Dienste und Werkzeuge verlassen zu müssen? Unsere Forschungsergebnisse sind sowohl als akademische Publikationen als auch als Open-Source Projekte verfügbar, die es künftigen Forschern und Praktikern ermöglichen, auf unseren Resultaten aufzubauen.

2.2 English

In this research project, we have explored how centralization of digital services and infrastructure can influence our privacy and digital self-determination, particularly related to interaction with smartphones as well as smart homes, and how tangible design objects can help users with improving their privacy awareness and practices. We present a variety of interaction methods, hard- and software toolkits, and user-focused studies on the perception of privacy, which are all united by the common concept of decentralization: how can we create state-of-the-art ubiquitous computing systems, such as a smart home or a tangible interaction environment, without relying on centralized and proprietary services and tools? Our research results are available as academic publications, but also in the form of multiple open-source projects, which are designed to enable future researchers and practitioners to easily build on our work.

3 Progress Report

3.1 Background and objectives of the project

This project aimed at investigating alternative infrastructures for ubiquitous computing ecosystems that do not rely on centralized services, such as cloud providers or optical tracking systems. In light of recent developments regarding reliability and trustworthiness of large-scale cloud corporations, this has proven to be a particularly timely topic.

3.2 Project-specific results and findings

Overall, our published results from this project can be grouped into three high-level categories: self-tracking and privacy, mobile and ubiquitous interaction, and tangible interaction toolkits. Unless noted otherwise, all publications have been jointly developed and written by at least one of the PhD students employed on the project, and the principal investigator.

- Self-Tracking & Privacy.

  Our research in this category reflects the shift of the project's original focus towards investigating and addressing service centralization and related privacy issues in the domains of "quantified self" and smart homes. One of our first publications, Rain-Maker [11] presented and evaluated a standalone tangible tool for self-managing work tasks and breaks without reliance on any cloud services. A more speculative research approach was taken for the more recent publications about VoxMox [1] and Frankie [7], both of which presented “provotypes” (***provo***cative proto***types***), i.e. functional design objects that are intended to challenge the users’ habits and thought patterns through provocative design choices. Both of these objects reflected facets of voice-based interaction (voice assistants such as Siri and Alexa for VoxMox, and voice-recorded journaling for Frankie), and attempted to nudge users into reflecting on the privacy implications of ubiquitous, cloud-connected recording devices. Finally, the “Privacy Covers” publication [3] used video vignettes showing various types of lens covers (manual, hybrid, automatic) to assess users’ attitudes towards managing privacy for smart home cameras. Surprisingly, users rated particularly the automatic covers as “creepy”, perhaps due to a perceived lack of control.

- Mobile and Ubiquitous Interaction

  In this context of interaction methods, we have contributed four individual sub-projects, which all mesh with the overall theme of decentralization – none of them rely on any centralized service and take great care to perform all data processing locally on a mobile device or wearable. The HeadsUp project [8] uses a regular smartphone to provide a wearable collision warning system, using ultrasound-based Doppler sensing to warn the user of approaching objects. Even though data is processed on-device, our approach only uses a negligible amount of computing resources and leaves plenty of room for concurrent everyday tasks. DesPat [10] collects image data from smartphones surveilling public spaces to assess pedestrian traffic and discover walkway patterns, e.g. for urban planning. This is particularly sensitive data, as it potentially contains personally-identifiable information; therefore, all image data is again processed locally on the smartphone and immediately discarded. Only the detected pedestrian positions are saved and aggregated over time. The TempoWatch [13] project focused on the specific use case of a dance lesson, in which the instructor needs an accessible way to control music playback speed without disrupting their interaction with the students. To this end, we developed a smartwatch app with a companion smartphone component that supported this goal, using an unobtrusive circular motion on the smartwatch that mapped to speed and enabled intuitive eyes-free control. Last but not least, SeedMarkers [12] loops back to the original research goal of decentralizing local tracking systems and provides a novel scheme for optical tracking markers that can be seamlessly and unobtrusively merged into the design of trackable objects, while still being detectable by a regular smartphone camera. In particular, SeedMarkers can be directly integrated into manufacturing processes using common prototyping methods such as 3D printing or laser-cutting.

- Tangible Interaction Toolkits

  The final category encompasses three projects which provide higher-level abstractions for specific forms of tangible interaction, enabling the easier creation of complex prototypes by providing a foundation on which to build those prototypes. First, the MirrorForge [9] toolkit provides a simulation and fabrication pipeline for free-form mirrors that can be integrated into projector- and/or camera-based user interfaces, e.g. to remap a regular camera's rectangular field of view to a 360° panoramic view, or to provide short-throw capabilities to a standard projector. In contrast, LensLeech [4] presents an approach to use patterned soft silicone widgets as input devices. These silicone objects can be directly put onto a camera lens, and by detecting the pattern using computer vision methods, a wide variety of interactions can be extracted (motion, rotation, squeezing, pushing, …). This approach enables augmenting existing devices with low-fidelity user interfaces such as action cameras, and also enables passive tangible interfaces that can be used as clip-on additions for e.g. smartphones. Finally, the SurfaceCast [5] framework provides building blocks for distributed, heterogeneous, shared interactive surfaces. These setups can be built from a variety of devices, such as large-scale interactive tabletops, mixed-reality headsets, tablets, or even plain desktop computers, and enable seamless and intuitive collaboration by distributed participants on a shared interactive surface. By using the peer-to-peer WebRTC protocol family for audio and video communication, we again ensure independence from proprietary protocols and cloud services.

In addition to the already-published results described above, we also have a working prototype of the "Lighthouse" standalone projection tangible envisioned in the original project proposal, which has however not yet been published in a peer-reviewed venue. This prototype consists of a can-sized tangible object that contains a pico-projector and a custom 360° mirror (designed using the MirrorForge toolkit) which redirects the projected image to cover a circular area around the entire tangible and enables ad-hoc projection on any planar surface. An upwards-looking camera connected to a Raspberry Pi inside the tangible is provided for planar tracking using an optical flow algorithm. The system is powered by an embedded lithium-ion battery pack.

3.3 Deviations from the original concept

The original project proposal focused primarily on decreasing dependence on *local* infrastructure, such as a 6-DoF optical tracking system for mixed-reality applications, or for collaborative computing using personal mobile devices. However, over the course of the project, our focus shifted towards addressing over-reliance on *cloud* infrastructure and related privacy issues, for example in the smart home context, and to exploring and analysing users' attitudes and preferences related to privacy-enhancing technologies.

3.4 Quality-Enhancing Measures

The most common quality-enhancing measures in research are triangulation, peer review, replication, and meta-analysis. In this project, we primarily used peer review of published research results as a quality measure, followed by triangulation (e.g. in the sense of using both quantitative and qualitative methods in the same study, to gather a more comprehensive understanding of the problem domain and the results than what would be possible by using one type of method alone). While we did not conduct any replication studies ourselves, we aimed for maximum transparency in our research results and have released all results, raw data, analysis code etc. as open data (see also next section). This allows for future replication studies to build on our results without having to first reconstruct large parts of our study protocol.

3.5 Handling of Research Data

As already committed to in the original project proposal, all publications have been made available as open access, and all research data generated during the studies and experiments has been made available on open research repositories. Specifically, we used Github for source code and hardware designs, Zenodo for immutable snapshots of Github repositories, and the Open Science Foundation (OSF.io) for questionnaire data, statistical analyses, and auxiliary data. All data on OSF is saved in standardized formats (CSV tables, R scripts, …) which do not require proprietary software to access. Although Github is usually not considered to meet the FAIR guidelines (repositories are not immutable and can be deleted), it is nevertheless a widely used collaboration platform for researchers. We have therefore opted to host the code on Github, but also created archival snapshots from the primary repositories using Zenodo.

3.6 Reusable and openly accessibly project results

As described in the previous section, we have released *all* project results on open repositories. The following software packages may be of particular interest for reuse by other researchers and practitioners:

- DesPat: a smartphone software package for decentralized pedestrian traffic tracking (https://github.com/volzotan/despat). In contrast to existing traffic counters, this system performs all image processing locally on the smartphone and never uploads or stores any image data - only the anonymous pedestrian trajectories are saved.
- Seedmarkers: shape-independent computer vision markers (https://github.com/volzotan/Seedmarkers) Marker-based visual tracking can be a distributed alternative to permanently-installed, centralized tracking systems (e.g. Vicon, ARTrack). However, the markers are usually blocky black-and-white patterns that are difficult to hide. Seedmarkers provides a toolkit for generating aesthetically pleasing markers that can be directly integrated into 3D-printed or laser-cut objects while adapting to the objects' shape.
- LensLeech: turning cameras into interactive controllers with soft silicone widgets (https://github.com/volzotan/LensLeech) Many small-scale devices with cameras (e.g. action cameras, small pocket cameras etc.) have very low-fidelity user interfaces. A LensLeech widget can be used to turn the camera lens itself into a multimodal user input device that allows for simultaneous rotation, translation, and push/pull input.
- Surfacecast: ubiquitous, cross-device interactive surfaces (https://github.com/floe/surfacecast) Previously, interactive surfaces have required expensive custom hardware such as touchscreen tabletop devices or depth cameras. With SurfaceCast, a wide variety of distributed devices (mixed-reality headsets, regular tablets, interactive whiteboards, or dedicated tabletops) can be merged into a single, shared, mixed-reality surface which enables ad-hoc collaboration at a distance.

- MirrorForge: a toolkit for designing and fabricating free-form optical-grade mirrors (https://github.com/volzotan/MirrorForge) This tool has evolved as a prerequisite for constructing the self-contained tangible projection tokens from the original project proposal. These tokens require specialized mirrors that would be cost-prohibitive to manufacture with conventional methods; the MirrorForge toolkit allows to design, evaluate, and construct these mirrors using modern fabrication tools.
- HeadsUp: an audio-based Doppler sensing toolkit for smartphones (https://github.com/mmbuw/headsup) This software uses the built-in microphone and speaker in an off-the-shelf smartphone to implement a Doppler sensing pipeline which can warn the user of imminent collisions with stationary or moving objects. As with DesPat, all signal processing is performed directly on the smartphone and no sensitive audio data is transmitted or retained.

3.7 Scientific events and communication measures

Several of our publications have been accompanied by demos and posters in which the individual prototypes have been presented to a live audience at various conferences (e.g. TEI and ISS, see also section 4.2). In addition, each project also has a companion Youtube video which has been posted publicly in order to increase the visibility of our projects and to introduce them to a wider audience. In addition, the MirrorForge paper [9] was honoured with the “Best Paper Award” at the TEI 2022 conference, and the Privacy Covers paper [3] was awarded a “Honourable Mention” at the DIS 2024 conference.

4 Published Project Results

4.1 Publications with scientific quality assurance

All publications below are open access, as committed to in the original grant proposal.

[1] Dr. Convenience Love or: How I Learned to Stop Worrying and Love my Voice Assistant Shalawadi, S. B., Echtler, F. & Raptis, D., 13 Okt. 2024, *NordiCHI '24: Proceedings of the 13th Nordic Conference on Human-Computer Interaction.* Association for Computing Machinery (ACM), s. 1-14, 14 s., 31. https://doi.org/10.1145/3679318.3685364

[2] From Reflection to Action: Enhancing Workplace Well-Being Through Digital Solutions
van Berkel, N., Visuri, A., Shalawadi, S. B., Evans, M. R., Tag, B. & Hosio, S., 26 Oct 2024, (accepted) In: Interacting with Computers. https://doi.org/10.1093/iwc/iwae049

[3] Manual, Hybrid, and Automatic Privacy Covers for Smart Home Cameras
Shalawadi, S., Getschmann, C., Berkel, N. V. & Echtler, F., 1 Jul 2024, *Proceedings of the 2024 ACM Designing Interactive Systems Conference, DIS 2024.* Vallgarda, A., Jonsson, L., Fritsch, J., Alaoui, S. F. & Le Dantec, C. A. (eds.). New York, USA: Association for Computing Machinery (ACM), p. 3453-3470 18 p. https://doi.org/10.1145/3643834.3661569

[4] LensLeech: On-Lens Interaction for Arbitrary Camera Devices
Getschmann, C. & Echtler, F., 11 Feb 2024, *TEI 2024 - Proceedings of the 18th International Conference on Tangible, Embedded, and Embodied Interaction.* Ciolfi, L. & Hogan, T. (eds.). New York, NY, USA: Association for Computing Machinery (ACM), p. 1-10 34. https://doi.org/10.1145/3623509.3633382

[5] SurfaceCast: Ubiquitous, Cross-Device Surface Sharing
Echtler, F., Maierhöfer, V., Hansen, N. B. & Wimmer, R., 31 Okt. 2023, Proceedings of the ACM on Human-Computer Interaction. 7, ISS, s. 286-308 23 s., 439. https://doi.org/10.1145/3626475

[6] A Longitudinal Analysis of Real-World Self-report Data
van Berkel, N., Shalawadi, S., Evans, M. R., Visuri, A. & Hosio, S., 28 Aug. 2023, *Proceedings of INTERACT 2023: 19th IFIP TC13 International Conference, Part III.* Abdelnour Nocera, J., Kristín Lárusdóttir, M., Petrie, H., Piccinno, A. & Winckler, M. (eds.). Springer, p. 611-632 22 p. (Lecture Notes in Computer Science, Vol. 14144 LNCS). https://doi.org/10.1007/978-3-031-42286-7_34

[7] Frankie: Exploring How Self-Tracking Technologies Can Go from Data-Centred to Human-Centred

Van Koningsbruggen, R., Shalawadi, S., Hornecker, E. & Echtler, F., 27 Nov. 2022, *Proceedings of the 21st International Conference on Mobile and Ubiquitous Multimedia: MUM '22.* Doring, T., Boll, S., Colley, A., Esteves, A. & Guerreiro, J. (red.). New York, NY, USA: Association for Computing Machinery (ACM), s. 243–250 8 s. (MUM '22). https://doi.org/10.1145/3568444.3568470

[8] HeadsUp: Mobile Collision Warnings through Ultrasound Doppler Sensing

Yaghoubisharif, N., Getschmann, C. & Echtler, F., 27 Nov. 2022, *Proceedings of the 21st International Conference on Mobile and Ubiquitous Multimedia: MUM '22.* Doring, T., Boll, S., Colley, A., Esteves, A. & Guerreiro, J. (red.). New York, NY, USA: Association for Computing Machinery (ACM), s. 200–207 8 s. (MUM '22). https://doi.org/10.1145/3568444.3568458

[9] MirrorForge: Rapid Prototyping of Complex Mirrors for Camera and Projector Systems

Getschmann, C., Mthunzi, E. M. & Echtler, F., 14 Feb. 2022, *TEI 2022 - Proceedings of the 16th International Conference on Tangible, Embedded, and Embodied Interaction.* New York, NY, USA: Association for Computing Machinery (ACM), s. 1-7 23. (TEI '22). https://doi.org/10.1145/3490149.3501329

[10] DesPat: Smartphone-Based Object Detection for Citizen Science and Urban Surveys

Getschmann, C. & Echtler, F., 26 Aug. 2021, I: i-com. 20, 2, s. 125-139 15 s. https://doi.org/10.1515/icom-2021-0012

[11] Rainmaker: A Tangible Work-Companion for the Personal Office Space

Shalawadi, S. B., Alnayef, A., van Berkel, N., Kjeldskov, J. & Echtler, F., 27 Sep. 2021, *MobileHCI '21: Proceedings of 23rd International Conference on Mobile Human-Computer Interaction : Mobile Apart, Mobile Together.* Association for Computing Machinery (ACM), s. 1-13 13 s. 39 https://doi.org/10.1145/3447526.3472032

[12] Seedmarkers: Embeddable Markers for Physical Objects

Getschmann, C. & Echtler, F., 2021, *TEI '21:Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction.* Association for Computing Machinery (ACM), s. 1-11 11 s. 26 https://doi.org/10.1145/3430524.3440645

[13] TempoWatch: A Wearable Music Control Interface for Dance Instructors

Roth, J., Getschmann, C., Ehlers, J. & Echtler, F., 2021, *TEI '21: Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction.* Association for Computing Machinery (ACM), s. 1-6 6 s. 55 https://doi.org/10.1145/3430524.3442461

4.2 Other publications and published results

[14] Demonstrating SurfaceCast: Ubiquitous, Cross-Device Surface Sharing

Echtler, F., Maierhöfer, V., Hansen, N. B. & Wimmer, R., 5 Nov. 2023, *ISS 2023 - Proceedings of the 2023 Conference on Interactive Surfaces and Spaces.* Biehl, J., Carter, S., Lucero, A., Makela, V. & Alt, F. (red.). New York, NY, USA: Association for Computing Machinery (ACM), s. 65–68 4 s.

[15] TouchBoard: Reimagining the Ergonomic Keyboard

Brams, A., Getschmann, C., Hornecker, E. & Echtler, F., 13 Dec. 2023, OSF Preprints, 11 s.

[16] Exploring Epileptic Seizure Detection with Commercial Smartwatches

Tobollik, T., Shalawadi, S., Getschmann, C. & Echtler, F., 22 Mar. 2021, *Proceedings of the 2021 IEEE International Conference on Pervasive Computing and Communications - Workshops and other Affiliated Events.* IEEE (Institute of Electrical and Electronics Engineers), s. 636-641 6 s. 9430866

4.3 Patents (applied for and granted)

Not applicable.