The Journal of Open Source Software

Ivy v1: A Data Acquisition System for Distributed Sensor Networks Supporting Remote Configuration and Software Updates

Moritz Makowski [1¶] **and Jia Chen** [1¶]

1 Environmental Sensing and Modeling, Technical University of Munich (TUM), Munich, Germany ¶ Corresponding author

DOI: 10.21105/joss.08862

Software

- Review
- Repository
- Archive

Editor: Neea Rusch

Reviewers:

- @ChitlangeSahas
- @cppraveen
- @brpat07

Submitted: 05 July 2025
Published: 25 September 2025

Summary

Distributed sensor networks monitor environmental conditions at remote locations. Each sensor node produces various time series data streams and system logs and sends this data to a central backend. A "sensor node" is an autonomous system collecting data from one or multiple sensors connected to it, operated 24/7 by a Data Acquisition System (DAS). As part of the ICOS Cities PAUL Project (European Commission, 2021), our group has developed a network of 20 autonomous GHG (greenhouse gas) sensor nodes (Aigner et al., 2024).

Since the software architecture of a DAS is independent of a specific sensor network, we present Ivy – a boilerplate for a DAS that supports configuring and updating itself remotely. Research teams building a new sensor network can use Ivy as a base for their own network-specific DAS. Ivy provides the core architecture, and users of the boilerplate only have to plug in their network-specific hardware logic to make it operational. Ivy is designed to be owned and customized: one can switch to another documentation system, add another backend, or remove unused parts of the boilerplate.

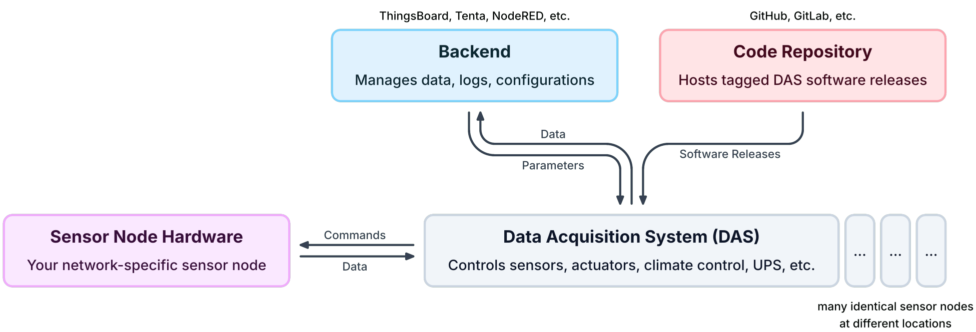

Figure 1: System architecture of a distributed sensor network based on a DAS like Ivy.

The architecture of Ivy shown in Figure 1 results from many iterations of the sensor networks our research group has built and operated (Aigner et al., 2023; Dietrich et al., 2021; TUM ESM et al., 2024). This publication aims to share a reference architecture of how a reliable DAS can be built, not claiming that Ivy is the only architecture for this use case.

Statement of Need and Similar Efforts

Continuous monitoring of our environment improves our understanding of anthropogenic impacts on the environment (IPCC, 2021, 2022). Distributed sensor networks are used to monitor atmospheric composition (Bares et al., 2019; Dietrich et al., 2021; Shusterman et al., 2016), forest ecosystems (Anderson-Teixeira et al., 2014; Zweifel et al., 2021, 2023), soil composition (Al-Yaari et al., 2018; Bogena et al., 2022; Dorigo et al., 2021), and air quality (Caubel et al., 2019; Popoola et al., 2018; Wenzel et al., 2021, 2025).

These sensor networks are typically built in a waterfall process: first, the DAS software is written, then the sensor nodes are deployed. However, many studies report post-deployment failures that can only be fixed by visiting sites in person (Bart et al., 2014; Tolle & Culler, 2005). A DAS allowing component failures and supporting remote reconfiguration and software updates enables teams to deploy their sensor nodes early and continuously improve their software remotely.

Many backends support collecting data from distributed sensor nodes. The FROST Server (Fraunhofer Institute of Optronics, System Technologies and Image Exploitation, 2024) implements the OGC SensorThings API specification (Open Geoscience Consortium, 2024). The Things Network (*The Things Network*, 2024) is a platform to manage LoRaWAN devices using The Things Stack (*The Things Stack*, 2024). Thingsboard (ThingsBoard, 2024a) and Tenta (Böhm et al., 2025) are similar backends offering MQTT and HTTP APIs to store and retrieve sensor network data.

Backends often provide client libraries (Makowski, 2024; ThingsBoard, 2024b; Vogl, 2023), but the complete code autonomously operating a specific network's sensor nodes is rarely published. This lack of open-sourced architectures makes it hard to assess how systems like this are built. Wireless Sensor Networks (WSNs), which have been widely studied (Kandris et al., 2020), consist of a "base station" communicating with many distributed "motes". However, Ivy focuses on the architecture of many distributed autonomous base stations, not motes. Basing a DAS on the Robot Operating System (ROS) (Macenski et al., 2022; Quigley et al., 2009) is a reasonable choice for environmental sensing applications. However, one still has to write the operational logic of the DAS because ROS only comes with the communication infrastructure. Both WSNs and ROS are complementary to Ivy since Ivy can operate a base station of a WSN or run inside a ROS node.

The Hermes software (TUM ESM et al., 2024) driving the Acropolis network has been open-sourced[1] and used from early 2023 to early 2025, enabling our group to deploy 38 software updates to the network. By now, this sensor network uses a modified variant of Hermes, Acropolis-Edge (TUM ESM et al., 2025), that runs the DAS inside a container and separates the DAS from the updater. However, both Hermes and Acropolis-Edge are not directly reusable for similar networks since they are tailored to the Acropolis network. Ivy refines the DAS architecture of Hermes and Pyra (Aigner et al., 2023; Dietrich et al., 2021) and makes it reusable for other sensor networks.

General System Design

Ivy uses a `config.json` file to store its active configuration. It can receive new configurations from the backend, change the config file it runs with, or perform a software update. The software update logic is built into the DAS, meaning it can also be updated. Figure 2 shows the update process of Ivy, which ensures that the DAS does not update itself to a version that does not run on the local hardware.

[1] https://github.com/tum-esm/hermes

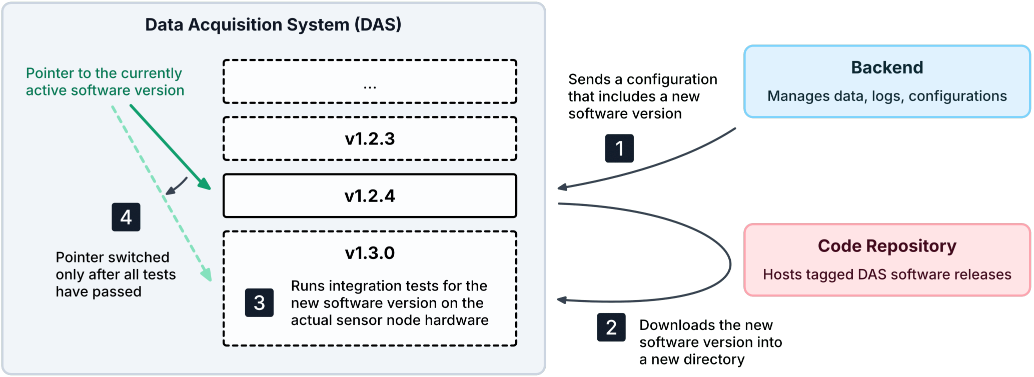

Figure 2: The software update process of Ivy.

Ivy comes with connectors for two backends out of the box – Thingsboard and Tenta – and uses the MQTT protocol to communicate with them. Nevertheless, Ivy is not bound to a specific backend or communication protocol. This flexibility prevents vendor lock-in and makes the boilerplate more reusable. We are happy to support more backends out of the box in the future, like Strapi (Strapi, 2024), Kuzzle (Kuzzle IO, 2024), or FROST. Furthermore, many utility functions have been moved to the `tum-esm-utils` Python package (Makowski et al., 2025).

Evolution of the Runtime Model

Whereas Hermes, Acropolis-Edge, and earlier versions of Pyra run much of the logic on a single thread, Ivy uses a fully parallel architecture, eliminating the possibility of one faulty component blocking other components. Each block of functionality running in an infinite loop is packaged into a "procedure". The "mainloop" is only responsible for managing procedure lifecycles and handling configuration changes. Starting with Pyra version 4.2, Pyra follows this parallel architecture of Ivy. Figure 3 shows the communication structure within Ivy.

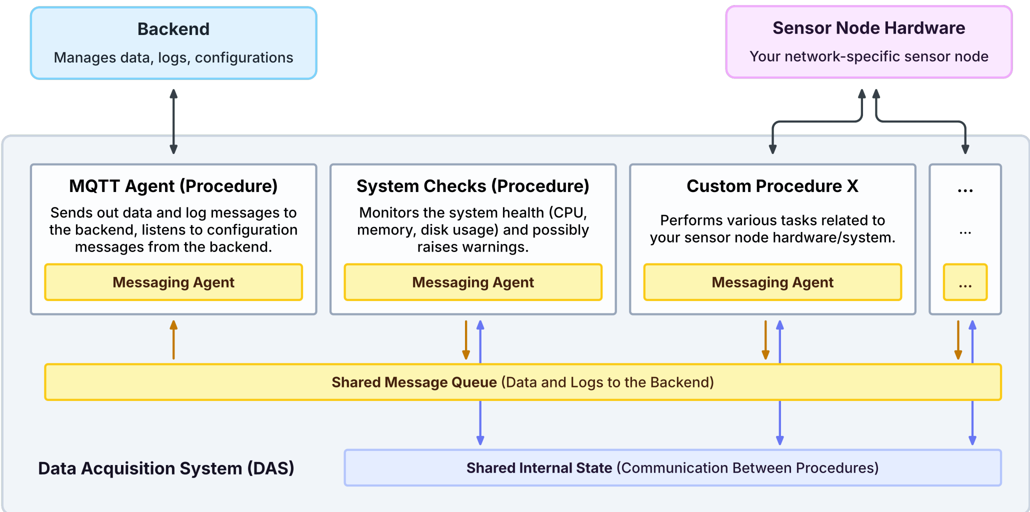

Figure 3: The communication between Ivy procedures.

Testing and Documentation

Ivy is statically typed and tested using Mypy (Python, 2024). Its test suite contains a test that tries to update a known working version to the current codebase and a test that tries to update the current codebase to a known working version. Ivy's API reference is generated automatically from the codebase and contains rendered schema references for all JSON files users interact with (configuration, local message archive, shared state).

Author Contributions

MM: developed the sensor side of Hermes, wrote the Ivy boilerplate, wrote the manuscript, works on Pyra; JC (PI): initialized, co-developed, and supervises the GHG sensor networks driven by Hermes and Pyra, helped with her expertise in environmental sensing, reviewed the manuscript.

Acknowledgement of Financial Support

This work is funded by the Horizon 2020 ICOS Cities PAUL Project under grant no. 101037319, and the ERC Consolidator Grant CoSense4Climate under grant no. 101089203.

References

Aigner, P., Kühbacher, D., Wenzel, A., Schmitt, A., Böhm, F., Makowski, M., Kürzinger, K., Laurent, O., Rubli, P., Grange, S., Emmenegger, L., & Chen, J. (2024). Advancing Urban Greenhouse Gas Monitoring: Development and Evaluation of a High-Density CO_2 Sensor Network in Munich. *ICOS Science Conference 2024*. https://www.icos-cp.eu/news-and-events/science-conference/icos2024sc/all-abstracts

Aigner, P., Makowski, M., Luther, A., Dietrich, F., & Chen, J. (2023). Pyra: Automated EM27/SUN Greenhouse Gas Measurement Software. *Journal of Open Source Software*, *8*(84), 5131. https://doi.org/10.21105/joss.05131

Al-Yaari, A., Dayau, S., Chipeaux, C., Aluome, C., Kruszewski, A., Loustau, D., & Wigneron, J.-P. (2018). The AQUI Soil Moisture Network for Satellite Microwave Remote Sensing Validation in South-Western France. *Remote Sensing*, *10*(11), 1839. https://doi.org/10.3390/rs10111839

Anderson-Teixeira, K. J., Davies, S. J., Bennett, A. C., Gonzalez-Akre, E. B., Muller-Landau, H. C., Joseph Wright, S., Abu Salim, K., Almeyda Zambrano, A. M., Alonso, A., Baltzer, J. L., Basset, Y., Bourg, N. A., Broadbent, E. N., Brockelman, W. Y., Bunyavejchewin, S., Burslem, D. F. R. P., Butt, N., Cao, M., Cardenas, D., … Zimmerman, J. (2014). CTFS-ForestGEO: A worldwide network monitoring forests in an era of global change. *Global Change Biology*, *21*(2), 528–549. https://doi.org/10.1111/gcb.12712

Bares, R., Mitchell, L., Fasoli, B., Bowling, D. R., Catharine, D., Garcia, M., Eng, B., Ehleringer, J., & Lin, J. C. (2019). The Utah urban carbon dioxide (UUCON) and Uintah Basin greenhouse gas networks: instrumentation, data, and measurement uncertainty. *Earth System Science Data*, *11*(3), 1291–1308. https://doi.org/10.5194/essd-11-1291-2019

Bart, M., Williams, D. E., Ainslie, B., McKendry, I., Salmond, J., Grange, S. K., Alavi-Shoshtari, M., Steyn, D., & Henshaw, G. S. (2014). High Density Ozone Monitoring Using Gas Sensitive Semi-Conductor Sensors in the Lower Fraser Valley, British Columbia. *Environmental Science & Technology*, *48*(7), 3970–3977. https://doi.org/10.1021/es404610t

Bogena, H. R., Schrön, M., Jakobi, J., Ney, P., Zacharias, S., Andreasen, M., Baatz, R., Boorman, D., Duygu, M. B., Eguibar-Galán, M. A., Fersch, B., Franke, T., Geris, J., González Sanchis, M., Kerr, Y., Korf, T., Mengistu, Z., Mialon, A., Nasta, P., … Vereecken, H. (2022). COSMOS-Europe: a European network of cosmic-ray neutron soil moisture sensors. *Earth System Science Data*, *14*(3), 1125–1151. https://doi.org/10.5194/essd-14-1125-2022

Böhm, F., Makowski, M., Aigner, P., & Chen, J. (2025). Tenta: Remote and real-time sensor network management. *Journal of Open Source Software*, *10*(105), 7311. https://doi.org/10.21105/joss.07311

Caubel, J. J., Cados, T. E., Preble, C. V., & Kirchstetter, T. W. (2019). A Distributed Network of 100 Black Carbon Sensors for 100 Days of Air Quality Monitoring in West Oakland, California. *Environmental Science & Technology*, *53*(13), 7564–7573. https://doi.org/10.1021/acs.est.9b00282

Dietrich, F., Chen, J., Voggenreiter, B., Aigner, P., Nachtigall, N., & Reger, B. (2021). MUCCnet: Munich urban carbon column network. *Atmospheric Measurement Techniques*, *14*(2), 1111–1126. https://doi.org/10.5194/amt-14-1111-2021

Dorigo, W., Himmelbauer, I., Aberer, D., Schremmer, L., Petrakovic, I., Zappa, L., Preimesberger, W., Xaver, A., Annor, F., Ardö, J., Baldocchi, D., Bitelli, M., Blöschl, G., Bogena, H., Brocca, L., Calvet, J.-C., Camarero, J. J., Capello, G., Choi, M., … Sabia, R. (2021). The International Soil Moisture Network: serving Earth system science for over a decade. *Hydrology and Earth System Sciences*, *25*(11), 5749–5804. https://doi.org/10.5194/hess-25-5749-2021

European Commission. (2021). *Pilot Application in Urban Landscapes - Towards integrated city observatories for greenhouse gases*. https://doi.org/10.3030/101037319

Fraunhofer Institute of Optronics, System Technologies and Image Exploitation. (2024). *FROST-server* (Version 2.4.2). https://github.com/FraunhoferIOSB/FROST-Server

IPCC. (2021). Summary for policymakers [Book Section]. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 3–31). Cambridge University Press. https://doi.org/10.1017/9781009157896.001

IPCC. (2022). Summary for policymakers [Book Section]. In H. O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama (Eds.), *Climate Change 2021: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 3–33). Cambridge University Press. https://doi.org/10.1017/9781009325844.001

Kandris, D., Nakas, C., Vomvas, D., & Koulouras, G. (2020). Applications of wireless sensor networks: An up-to-date survey. *Applied System Innovation*, *3*(1), 14. https://doi.org/10.3390/asi3010014

Kuzzle IO. (2024). *Kuzzle* (Version 2.34.0). https://github.com/kuzzleio/kuzzle

Macenski, S., Foote, T., Gerkey, B., Lalancette, C., & Woodall, W. (2022). Robot operating system 2: Design, architecture, and uses in the wild. *Science Robotics*, *7*(66). https://doi.org/10.1126/scirobotics.abm6074

Makowski, M. (2024). *Tenta Python Client* (Version 0.1.5). https://github.com/tum-esm/tenta-client

Makowski, M., Klappenbach, F., & Chen, J. (2025). *TUM ESM Python Utilities* (Version 2.8.0). https://doi.org/10.5281/zenodo.14284949

Open Geoscience Consortium. (2024). *OGC SensorThings API*. https://www.ogc.org/standard/sensorthings/

Popoola, O. A. M., Carruthers, D., Lad, C., Bright, V. B., Mead, M. I., Stettler, M. E. J., Saffell, J. R., & Jones, R. L. (2018). Use of networks of low cost air quality sensors to quantify air quality in urban settings. *Atmospheric Environment*, *194*, 58–70. https://doi.org/10.1016/j.atmosenv.2018.09.030

Python. (2024). *Mypy* (Version 1.13.0). https://github.com/python/mypy

Quigley, M., Gerkey, B., Conley, K., Faust, J., Foote, T., Leibs, J., Berger, E., Wheeler, R., & Ng, A. (2009, May). ROS: An open-source robot operating system. *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), Workshop on Open Source Robotics*.

Shusterman, A. A., Teige, V. E., Turner, A. J., Newman, C., Kim, J., & Cohen, R. C. (2016). The BErkeley Atmospheric CO_2 Observation Network: initial evaluation. *Atmospheric Chemistry and Physics*, *16*(21), 13449–13463. https://doi.org/10.5194/acp-16-13449-2016

Strapi. (2024). *Strapi* (Version 5.4.0). https://github.com/strapi/strapi

The Things Network. (2024). https://www.thethingsnetwork.org/

The Things Stack. (2024). https://www.thethingsindustries.com/stack/

ThingsBoard. (2024a). *ThingsBoard* (Version 3.8.1). https://github.com/thingsboard/thingsboard

ThingsBoard. (2024b). *ThingsBoard client python SDK* (Version 1.10.10). https://github.com/thingsboard/thingsboard-python-client-sdk

Tolle, G., & Culler, D. (2005). Design of an application-cooperative management system for wireless sensor networks. *Proceeedings of the Second European Workshop on Wireless Sensor Networks, 2005.* https://doi.org/10.1109/ewsn.2005.1462004

TUM ESM, Aigner, P., Böhm, F., Frölich, L., Makowski, M., Schmitt, A., & Chen, J. (2024). *Hermes, Professorship of Environmental Sensing and Modeling, Technical University of Munich* (Version 1.0.1). https://github.com/tum-esm/hermes

TUM ESM, Aigner, P., Böhm, F., Frölich, L., Makowski, M., Schmitt, A., & Chen, J. (2025). *ACROPOLIS-edge, Professorship of Environmental Sensing and Modeling, Technical University of Munich* (Version 0.0.95). https://github.com/tum-esm/ACROPOLIS-edge

Vogl, J. (2023). *Python client library for FROST* (Version 1.1.45). https://github.com/FraunhoferIOSB/FROST-Python-Client

Wenzel, A., Chen, J., Dietrich, F., Thekkekara, S. T., Zollitsch, D., Voggenreiter, B., Setili, L., Wenig, M., & Keutsch, F. N. (2021). *Stand-alone low-cost sensor network in the inner city of Munich for modeling urban air pollutants*. https://doi.org/10.5194/egusphere-egu21-15182

Wenzel, A., Chen, J., Klama, T., Böhm, F., Angleitner, M., & Lobmaier, R. (2025). *Towards high-resolution air pollutants sensing through dense low-cost sensor networks – a case study in Munich*. https://doi.org/10.5194/egusphere-egu25-16784

Zweifel, R., Etzold, S., Basler, D., Bischoff, R., Braun, S., Buchmann, N., Conedera, M., Fonti, P., Gessler, A., Haeni, M., Hoch, G., Kahmen, A., Köchli, R., Maeder, M., Nievergelt, D., Peter, M., Peters, R. L., Schaub, M., Trotsiuk, V., … Eugster, W. (2021). TreeNet–The Biological Drought and Growth Indicator Network. *Frontiers in Forests and Global Change*, *4*. https://doi.org/10.3389/ffgc.2021.776905

Zweifel, R., Pappas, C., Peters, R. L., Babst, F., Balanzategui, D., Basler, D., Bastos, A., Beloiu, M., Buchmann, N., Bose, A. K., Braun, S., Damm, A., D'Odorico, P., Eitel, J. U. H., Etzold, S., Fonti, P., Rouholahnejad Freund, E., Gessler, A., Haeni, M., … Sterck, F. (2023). Networking the forest infrastructure towards near real-time monitoring – a white paper. *Science of The Total Environment*, *872*, 162167. https://doi.org/10.1016/j.scitotenv.2023.162167