Pallet to Simulation - Synthetic Data from Physics Simulations: A Viable Alternative for Pallet Activity Recognition?

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Background, motivation and approach

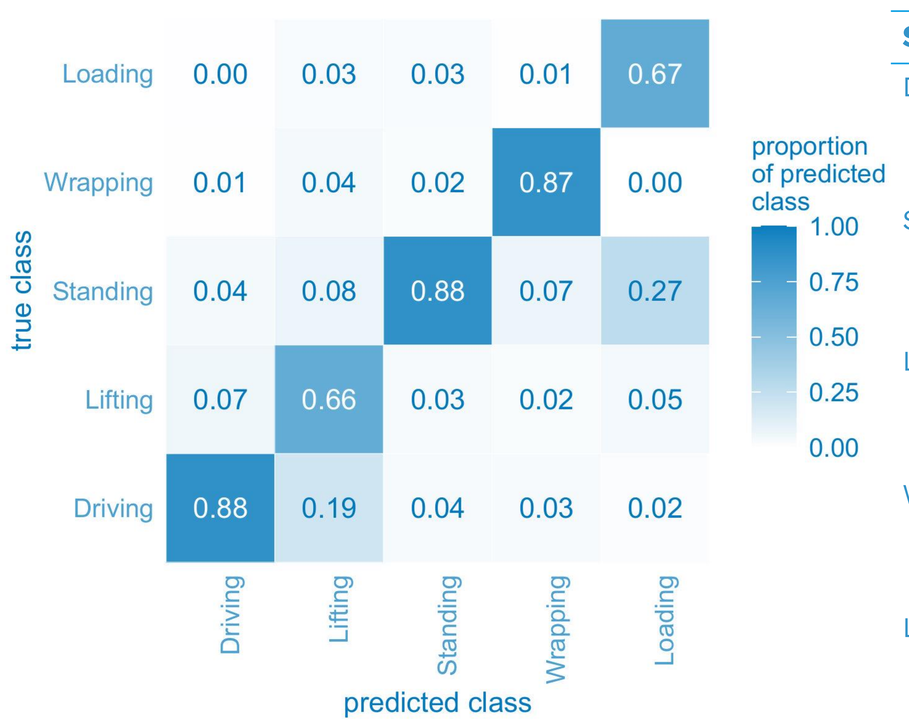
Pallets are one of the most important load carriers for supply chains. Yet, continuously tracking activities such as 'Driving', 'Lifting' or 'Handling' along their life cycle is hardly possible. The research approach is to classify these logistics activities using IMU sensor data, to enable in-depth analysis of transport chains.

Fig 1: Overview of research approach

The high variability of logistical influences—such as vehicle types, loading scenarios, and process flows— result in a need to have a very large and diverse set of training data. To deal with this Pal2Sim pursues the approach of generating synthetic sensor data using physical simulation with NVIDIA Isaac Sim™. The aim is to examine the extent to which this artificially generated data can close the gap in real data sets and thus enable the comprehensive detection of logistics activities.

Classification of real data

In the preliminary research[3,4], data sets were recorded under laboratory conditions and published as *Sensor-based Pallet Activity Recognition in Logistics (SPARL)*[1,2] dataset. Using a random forest classifier, it was shown that even small amounts of data are sufficient to robustly recognize most classes and their superclasses. Figure 2 shows the confusion matrix of the superclasses as well as the developed taxonomy.



Superclass	Minority Classes
Driving	Driving (straight), Driving (curve), Lifting and driving
Standing	Standing, Docking, Forks entering or leaving the pallet, Wrapping preperation, Rotation
Lifting	Lifting (raising), Lifting (lowering), Lifting (tilting)
Wrapping	Wrapping (stretch curler)
Loading	Loading (with goods)

Fig 2: Confusion matrix and taxonomy of SPARL[1,2]

From a logistical perspective, it is most important to identify the superclasses. A more detailed breakdown into minority classes is only of interest in rare cases. Figure 3 shows an example graph of the SPARL[1,2] dataset in which the taxonomy has been annotated (true) and the prediction has been made by the classifier (predicted).

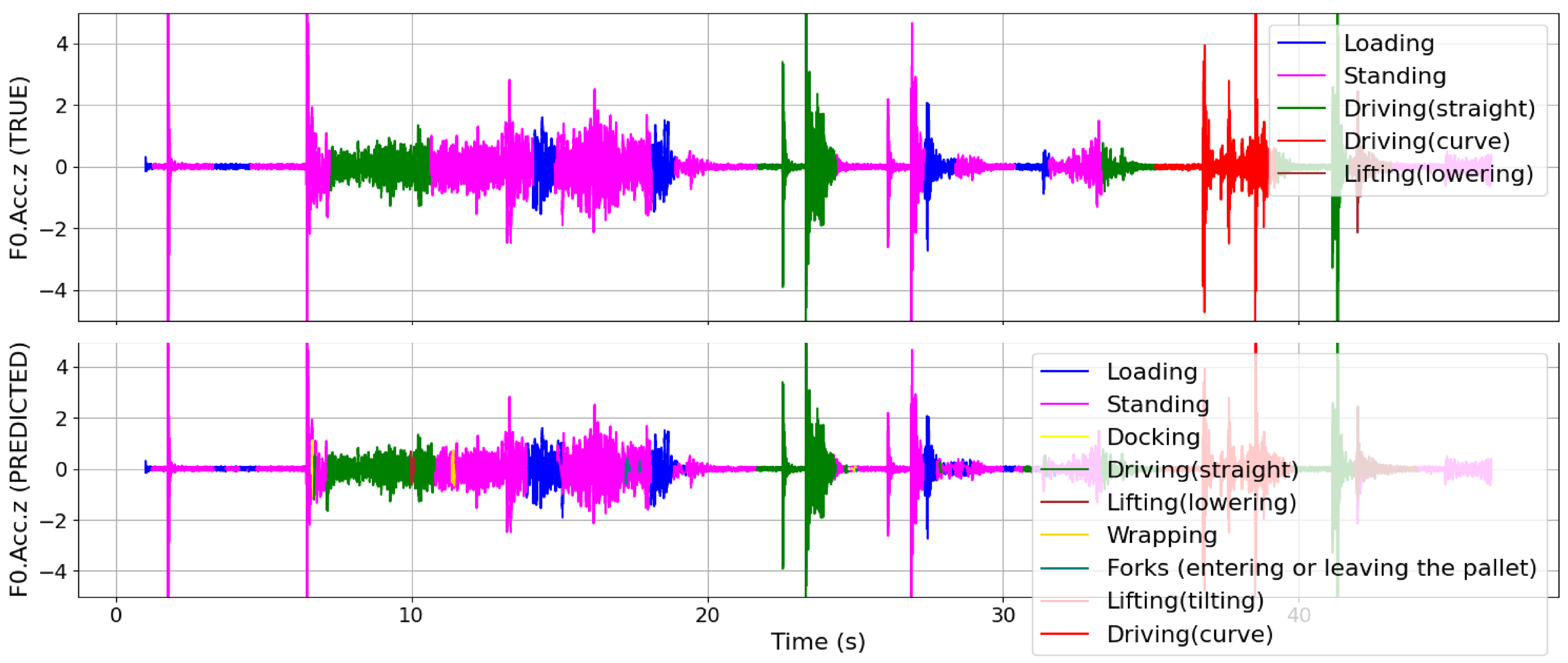


Fig 3: Plots of true classes and predicted classes of SPARL[1,2]

The diagrams show that most classes are predicted robustly and are therefore sufficient. However, an analysis of the mean feature importances of the used random forest model shows that no feature exceeds an importance of more than 0,0x. This suggests that the model has limited ability to capture the high-dimensional relationships in the IMU data.

Experimental procedure

In order to compare the synthetic data with real-world data, the SPARL[1,2] data sets were expanded to include recordings taken in a real industrial environment at the Rhenus Logistics warehouse in Wesel.

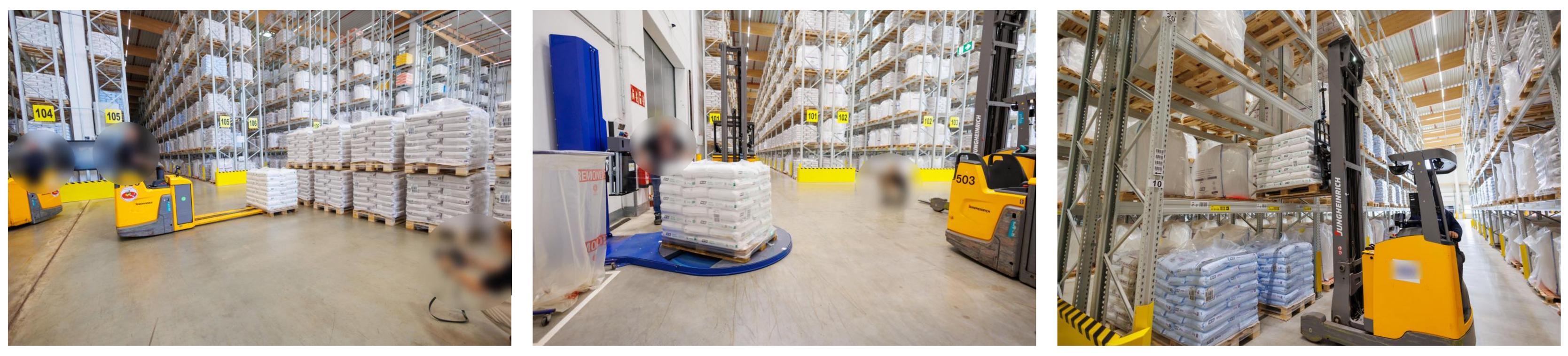


Fig 4: Data collection process at Rhenus Logistics

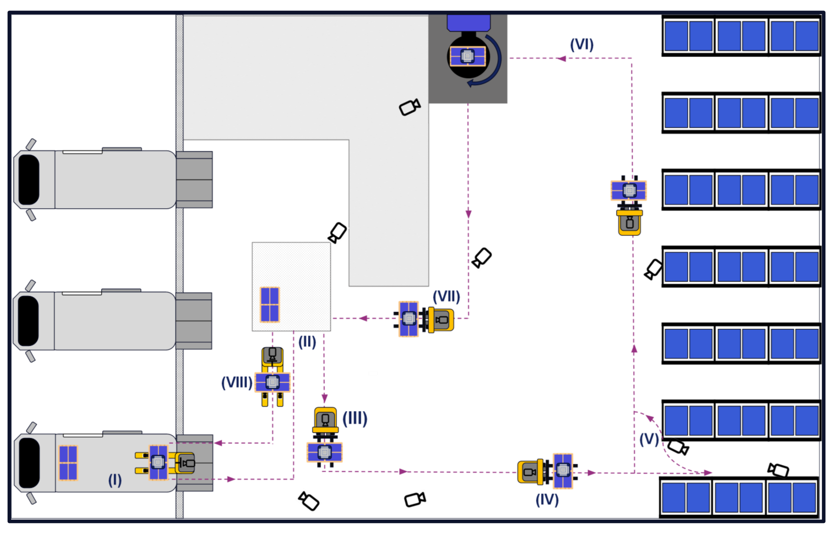


Fig 5: Data collection procedure overview

An overview of the test procedure can be seen in Figure 5. The usual process of unloading goods from a truck with a hand pallet truck (I), parking in a buffer zone (II), pick up with a Forklift truck (III), storing in a high-bay warehouse (IV), unloading (V), securing the load (VI), parking in the goods issue area (VII), and transferring the pallet back to a truck (VIII) was recorded. This process was carried out several times with two test subjects.

Examination of the Sim2Real Gap (work in prog.)

In order to compare the real data set with the synthetic data, the test procedure described above was simulated in NVIDIA Isaac Sim™. In particular, the properties of the pallet and the load as well as the driving characteristics were simulated. After only rough parameter tuning of the simulation, a first comparison with the real data was made in order to perform targeted tuning of the parameters and iteratively improve the simulated database. The comparison shows that the simulated vibration behaves similarly to the actual vibrations in the acceleration-time range (see Fig. 3). An examination in the frequency domain (Fig. 6), however, reveals the differences in the dynamics of both oscillations.

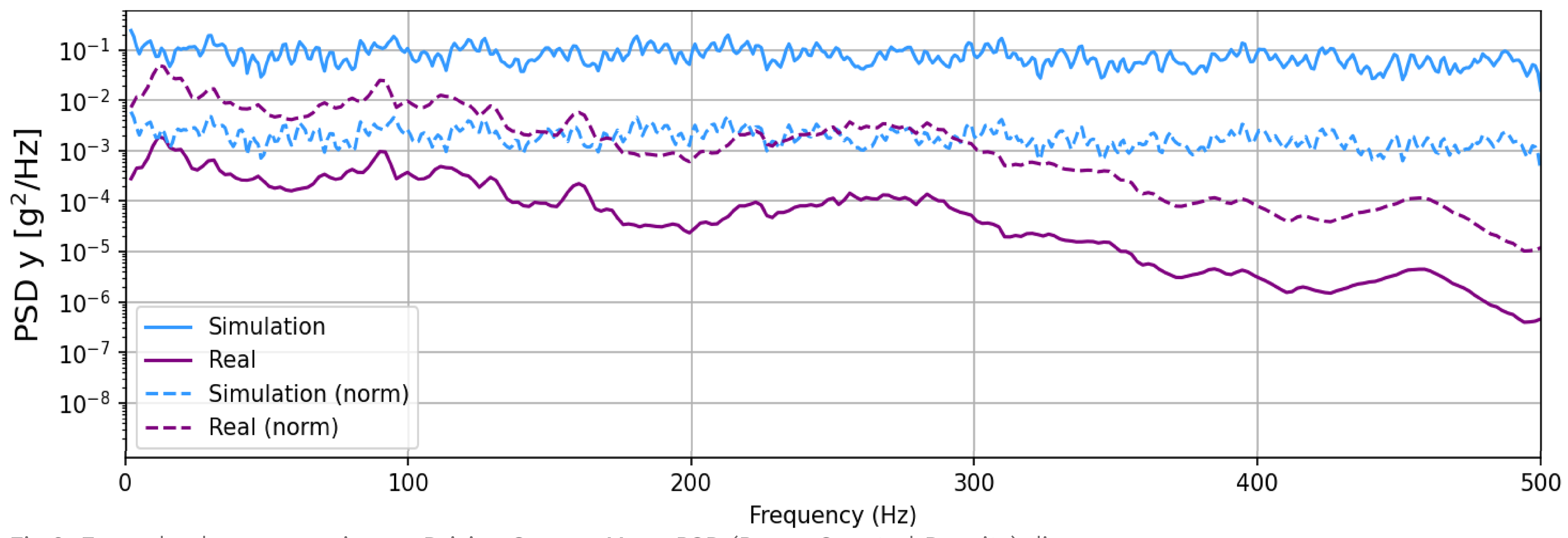


Fig 6: Example class comparison – Driving Curve - Mean PSD (Power Spectral Density) diagram

The simulation systematically overestimates the spectral power and shows an almost static behavior across the frequency band, while the real data exhibits strong frequency-dependent attenuation. Even after normalization, characteristic differences remain between simulated and real data, highlighting the Sim2Real gap.

Interim conclusion & next steps

The untuned simulation has not yet the same characteristics as the real data. To achieve a more realistic representation, careful parameter tuning of the simulation is required. In addition, post-processing steps such as adding noise may be necessary to better capture real-world dynamics, because real data always exhibits variance. The next steps are to iteratively improve the simulation and determine whether the synthetic data can supplement the training data for the classification of logistics activities. In addition, it´s going to be examined whether deep learning models could achieve higher predictive performance compared to random forests due to their ability to utilize local and temporal patterns.

Cooperation

RHENUS LOGISTICS

References

1. Franke, S., Bommert, A., Brandt, M. J., Kuhlmann, J. L., Olivier, M.-C., Schorning, K., Roidl, M., Reining, C., & Kirchheim, A. (2024). Sensor-based Pallet Activity Recognition in Logistics (SPARL Version 1) - A multi-modal Dataset (Version 1), [Data set]. Zenodo. https://doi.org/10.5281/zenodo.11280959
2. Franke, S., Bommert, A., Brandt, M. J., Kuhlmann, J. L., Olivier, M.-C., Schorning, K., Roidl, M., Reining, C., & Kirchheim, A. (2024). Sensor-based Pallet Activity Recognition in Logistics (SPARL Version 2) - A multi-modal Dataset (Version 2) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.13318882
3. Franke, S., Bommert, A., Brandt, M. J., Kuhlmann, J. L., Olivier, M.-C., Schorning, K., ... Kirchheim, A. (2024). Data-driven, sensor-based taxonomy for environmental life cycle assessment of pallets. Logistics Journal: Proceedings, (20). https://doi.org/10.2195/lj_proc_franke_en_202410_01
4. S. Franke, A. Bommert, M. J. Brandt, J. L. Kuhlmann, M.-C. Olivier, K. Schorning, C. Reining, and A. Kirchheim, "Smart pallets: Towards event detection using imus," in 2024 IEEE 29th International Conference on Emerging Technologies and Factory Automation (ETFA). IEEE, 2024, pp. 1–4.

Pal2Sim dataset challenge

Interested in our project? Join the challenge with our dataset!

- **Challenge 1:** Can you outperform our classifier?
- **Challenge 2:** Can you bridge the Sim2Real gap?
- **Challenge 3:** Can you develop an automatic annotation tool?

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