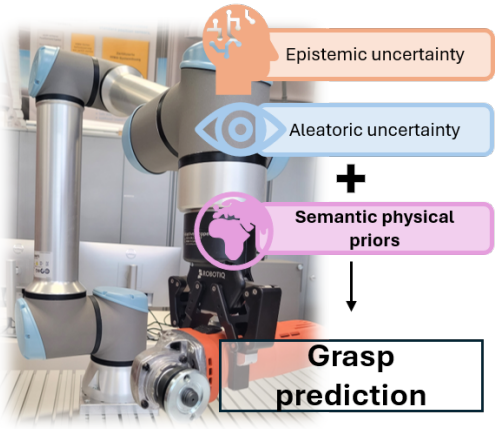
Semantic Physical Priors for Uncertainty-Aware Robotic Grasp Prediction

Master Thesis

Motivation



Learning-based grasp prediction usually relies mainly on geometric observations such as RGB-D images or point clouds. However, grasp stability also depends on latent physical properties that may not be observable from geometry alone, for example the center of mass, mass distribution, friction, stiffness, or whether an object is filled. A grasp predictor can therefore be highly confident while still being wrong because its training data, especially simulation data, does not represent the true physical properties of the object. At the same time, semantic knowledge about an object can provide useful physical priors. For example, knowing that an object is a hammer provides information about a likely non-uniform mass distribution even if the exact physical parameters are unknown. The central idea of this thesis is to use such semantic physical priors as an additional uncertainty or confidence signal for grasp prediction, rather than treating them as exact ground-truth properties.

Starting Point

The thesis starts from an existing uncertainty-aware 6-DoF grasp-prediction/planning method that already distinguishes **aleatoric uncertainty** (uncertainty caused by noisy or ambiguous observations) from **epistemic uncertainty** (uncertainty caused by limited model knowledge or distribution shift). The student is not expected to develop a complete grasp detector from scratch. Instead, the existing model serves as a baseline whose grasp-quality and uncertainty estimates are extended by semantic physical information.

Research Objective

The main research question is: *How can semantic physical priors be integrated into the confidence or uncertainty estimate of an existing grasp predictor such that they appropriately modify grasp quality and ranking?*

The physical prior could, for example, **decrease** confidence when semantic physical knowledge contradicts an otherwise confident geometry-based grasp uncertainty, **increase** confidence when it provides complementary evidence, or **shift grasp rankings** toward physically more plausible grasp locations. A central challenge is to represent the semantic prior itself as uncertain rather than as an exact physical value.

Research Outlook

A natural follow-up problem, but not a requirement of this thesis, is **experience-based adaptation of the semantic physical prior**. After executing grasps, tactile, force/torque, slip, or proprioceptive observations could be used to update the initial semantic belief about properties such as center of mass. This would turn the semantic estimate into an experience-grounded physical belief and enable the robot to refine its grasp confidence over repeated interactions.

Requirements

- Strong Python and machine-learning/deep-learning skills, experience with PyTorch or similar libraries
- Basic robotics

Starting Literature

1. Shi, Y., Welte, E., Gilles, M., & Rayyes, R. (2025). vMF-Contact: Uncertainty-aware Evidential Learning for Probabilistic Contact-grasp in Noisy Clutter. arXiv:2411.03591.
2. Fang, H.-S., Wang, C., Fang, H., Gou, M., Liu, J., Yan, H., Liu, W., Xie, Y., & Lu, C. (2023). AnyGrasp: Robust and Efficient Grasp Perception in Spatial and Temporal Domains. IEEE Transactions on Robotics, 39(5), 3929-3945.
3. Xie, W., Valentini, M., Lavering, J., & Correll, N. (2025). DeliGrasp: Inferring Object Properties with LLMs for Adaptive Grasp Policies. Proceedings of the Conference on Robot Learning, PMLR 270, 1290-1309.
4. Li, M., Hang, K., Kragic, D., & Billard, A. (2016). Dexterous Grasping under Shape Uncertainty. Robotics and Autonomous Systems, 75, 352-364.

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