

UNIVERSITY OF ALICANTE

PHD THESIS

TBD

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*A thesis submitted in fulfilment of the requirements
for the degree of Doctor of Philosophy*

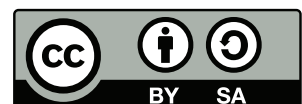
in the

3D Perception Lab
Department of Computer Technology

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“Will robots inherit the earth? Yes, but they will be our children.”

Marvin Minsky

Abstract

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Resumen

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Acknowledgements

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List of Acronyms

3D three-dimensional

CNN Convolutional Neural Network

Introduction

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1.1 Motivation

1.2 Approach

1.3 Contributions

1.4 Co-Authored Papers

This thesis is the result of continuous effort throughout the last years. Such efforts have sometimes crystallized in form of co-authored publications and conference talks.

1.4.1 Chapter 2

- Alberto Garcia-Garcia, Francisco Gomez-Donoso, Jose Garcia-Rodriguez, et al. “PointNet: A 3D Convolutional Neural Network for real-time object class recognition”. In: *2016 International Joint Conference on Neural Networks, IJCNN 2016, Vancouver, BC, Canada, July 24-29, 2016*. 2016, pp. 1578–1584. DOI: [10.1109/IJCNN.2016.7727386](https://doi.org/10.1109/IJCNN.2016.7727386). URL: <https://doi.org/10.1109/IJCNN.2016.7727386>
- Alberto Garcia-Garcia, Jose Garcia-Rodriguez, Sergio Orts-Escolano, et al. “A study of the effect of noise and occlusion on the accuracy of convolutional neural networks applied to 3D object recognition”. In: *Computer Vision and Image Understanding* 164 (2017), pp. 124–134. DOI: [10.1016/j.cviu.2017.06.006](https://doi.org/10.1016/j.cviu.2017.06.006). URL: <https://doi.org/10.1016/j.cviu.2017.06.006>
- Francisco Gomez-Donoso, Alberto Garcia-Garcia, Jose Garcia-Rodriguez, et al. “LonchaNet: A Sliced-based CNN Architecture for Real-time 3D Object Recognition”. In: *2017 International Joint Conference on Neural Networks, IJCNN 2017, Anchorage, Alaska, May 14-19, 2017*. 2017. URL: <https://ieeexplore.ieee.org/document/7965883/>

1.4.2 Chapter 3

- Alberto Garcia-Garcia, Jose Garcia-Rodriguez, Sergio Orts-Escolano, et al. “A study of the effect of noise and occlusion on the accuracy of convolutional neural networks applied to 3D object recognition”. In: *Computer Vision and Image Understanding* 164 (2017), pp. 124–134. DOI: [10.1016/j.cviu.2017.06.006](https://doi.org/10.1016/j.cviu.2017.06.006). URL: <https://doi.org/10.1016/j.cviu.2017.06.006>
- Alberto Garcia-Garcia, Pablo Martinez-Gonzalez, Sergiu Oprea, et al. “The RobotriX: An eXtremely Photorealistic and Very-Large-Scale Indoor Dataset of Sequences with Robot Trajectories and Interactions”. In: *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE. 2018, pp. 6790–6797. URL: <https://ieeexplore.ieee.org/abstract/document/8594495>
- TODO: UnrealROX

1.4.3 Chapter 4

- TODO: TactileGCN

1.4.4 Other

During the years spent working on the main topics of this thesis, several collaborations and side works were carried out that also were published either as journal papers, conference proceedings, or preprints:

- Sergiu Oprea, Alberto Garcia-Garcia, Jose Garcia-Rodriguez, et al. “A Recurrent Neural Network based Schaeffer Gesture Recognition System”. In: *2017 International Joint Conference on Neural Networks, IJCNN 2017, Anchorage, Alaska, May 14-19, 2017*. 2017. URL: <https://ieeexplore.ieee.org/document/7965885/>

- Francisco Gomez-Donoso, Sergio Orts-Escolano, Alberto Garcia-Garcia, et al. "A robotic platform for customized and interactive rehabilitation of persons with disabilities". In: *Pattern Recognition Letters* 99 (2017), pp. 105–113. DOI: [10.1016/j.patrec.2017.05.027](https://doi.org/10.1016/j.patrec.2017.05.027). URL: <https://doi.org/10.1016/j.patrec.2017.05.027>
- Sergiu Oprea, Alberto GarciaGarcia, Sergio OrtsEscolano, et al. "A long short-term memory based Schaeffer gesture recognition system". In: *Expert Systems* 0.0 (2017), e12247. DOI: [10.1111/exsy.12247](https://doi.org/10.1111/exsy.12247). URL: <https://onlinelibrary.wiley.com/doi/abs/10.1111/exsy.12247>
- Alberto Garcia Garcia, Andreas Beckmann, and Ivo Kabadshow. "Accelerating an FMM-Based Coulomb Solver with GPUs". In: *Software for Exascale Computing-SPPEXA 2013-2015*. Springer, 2016, pp. 485–504. URL: https://link.springer.com/chapter/10.1007/978-3-319-40528-5_22
- Alberto Garcia-Garcia, Sergio Orts-Escolano, Sergiu Oprea, et al. "Multi-sensor 3D object dataset for object recognition with full pose estimation". In: *Neural Computing and Applications* 28 (2016), pp. 941–952. ISSN: 1433-3058. DOI: [10.1007/s00521-016-2224-9](https://doi.org/10.1007/s00521-016-2224-9). URL: <http://dx.doi.org/10.1007/s00521-016-2224-9>
- Marcelo Saval-Calvo, Jorge Azorin-Lopez, Andres Fuster-Guillo, et al. "Evaluation of sampling method effects in 3D non-rigid registration". In: *Neural Computing and Applications* 28 (2016), pp. 953–967. ISSN: 1433-3058. DOI: [10.1007/s00521-016-2258-z](https://doi.org/10.1007/s00521-016-2258-z). URL: <http://dx.doi.org/10.1007/s00521-016-2258-z>
- Sergio Orts-Escolano, Jose Garcia-Rodriguez, Miguel Cazorla, et al. "Bioinspired point cloud representation: 3D object tracking". In: *Neural Computing and Applications* 29 (2016), pp. 663–672. ISSN: 1433-3058. DOI: [10.1007/s00521-016-2585-0](https://doi.org/10.1007/s00521-016-2585-0). URL: <https://doi.org/10.1007/s00521-016-2585-0>
- Alberto Garcia-Garcia, Sergio Orts-Escolano, Jose Garcia-Rodriguez, et al. "Interactive 3D object recognition pipeline on mobile GPGPU computing platforms using low-cost RGB-D sensors". In: *Journal of Real-Time Image Processing* 14 (2016), pp. 585–604. ISSN: 1861-8219. DOI: [10.1007/s11554-016-0607-x](https://doi.org/10.1007/s11554-016-0607-x). URL: <https://doi.org/10.1007/s11554-016-0607-x>
- Higinio Mora, Jerónimo M Mora-Pascual, Alberto Garcia-Garcia, et al. "Computational analysis of distance operators for the iterative closest point algorithm". In: *PloS one* 11.10 (2016), e0164694. URL: <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0164694>
- Sergio Orts-Escolano, Jose Garcia-Rodriguez, Vicente Morell, et al. "3D Surface Reconstruction of Noisy Point Clouds Using Growing Neural Gas: 3D Object/Scene Reconstruction". In: *Neural Processing Letters* 43 (2015), pp. 401–423. DOI: [10.1007/s11063-015-9421-x](https://doi.org/10.1007/s11063-015-9421-x). URL: <http://dx.doi.org/10.1007/s11063-015-9421-x>
- Sergio Orts-Escolano, Jose Garcia-Rodriguez, Jose Antonio Serra-Perez, et al. "3D model reconstruction using neural gas accelerated on GPU". in: *Applied Soft Computing* 32 (2014), pp. 87–100. DOI: [10.1016/j.asoc.2015.03.042](https://doi.org/10.1016/j.asoc.2015.03.042). URL: <http://dx.doi.org/10.1016/j.asoc.2015.03.042>

- TODO: ICP

1.5 Thesis Structure

Object Recognition

Abstract

In this chapter, we address the problem of object class recognition. To approach this challenge, we rely on the geometric information provided by 3D object representations such as point clouds. Furthermore, we focus on learning-based methods to distinguish objects from different classes while capturing the variability of shape of different objects which belong to the same class. More specifically, we leverage deep learning for such task. The chapter begins introducing and formulating the object recognition task in Section 2.1 followed by a review of the most relevant literature in Section 2.2. After that, we present our first proposal towards 3D object recognition using Convolutional Neural Networks (CNNs), namely PointNet, in Section 2.3. Later, PointNet is improved and thoroughly tested in adverse conditions with noise and occlusion throughout the study in Section 2.4. Next, LonchaNet is introduced in Section 2.5 as the last iteration of our system that incorporates all the lessons learned by the previous work. Finally, Section 2.6 draws conclusions and sets future lines of research.

2.1 Introduction

Object recognition is fundamental to computer vision and despite the progress achieved during the last years, it still remains a challenging area of research. Arguably, most of the interest in object recognition is due to its usefulness for robotics.

In that regard, recognizing objects is one of the problems that must be solved to achieve total visual scene understanding. Such deeper and better knowledge of the environment eases and enables the execution of a wide variety of more complex tasks. For instance, accurately recognizing objects in a room can be extremely useful for any robotic system that navigates within indoor environments. Due to the unstructured nature of those environments, autonomous robots need to do reasoning grounded in the dynamic real world. In other words, they need to understand the information captured by their sensors to perform tasks such as grasping, navigation, mapping, or even providing humans with information about their surroundings. Identifying the classes to which objects belong is one key step to enhance the aforementioned capabilities.

Despite the easy intuitive interpretation of the problem, its inherent difficulty can be misleading. We humans recognize numerous objects in difficult settings (e.g., different points of view, occlusion, or clutter) with little to no effort. However, approaching that problem is not that easy for a computer and taking into account all the possible settings and combinations of external factors renders this task a difficult one to solve efficiently and with high precision (which is often required in numerous application scenarios).

From a formal point of view, the object recognition task can be formulated as follows: given an image $\mathcal{I}^{H \times W}$ in which an object \mathcal{O} appears, which can be either a gray-scale or RGB array of W pixels in width and H pixels in height, the goal is to predict the class of the object $\mathcal{L}_{\mathcal{O}}$ from a set of N predefined object classes $\mathcal{L} = \{\mathcal{L}_0, \mathcal{L}_1, \dots, \mathcal{L}_{N-1}\}$.

Most of the classic literature of this topic tackled such problem by devising hand-crafted feature descriptors that are extracted on certain keypoints detected over the bidimensional image and later used either to compare them against pre-existing object descriptors in a database to match them to a certain class or either to feed them as input to a shallow machine learning architecture that learns to classify those descriptors to predict the class of the object that appears in the image. That paradigm shifted recently due to the success of deep learning architectures that are able to exploit their feature learning capabilities to avoid the need of hand engineering descriptors while achieving unprecedented accuracy levels. Furthermore, the adoption and spread of depth sensors has also added a literally new dimension to learn from to boost performance. The approaches introduced in this thesis are part of that cutting-edge trend that takes advantage of the additional geometric information facilitated by commodity range scanners to perform learning over them using deep architectures. A more detailed review of the field, from the very beginning to the current trends using 3D data and deep neural networks, is performed in Section 2.2.

After that literature review, we start describing our first approach to perform object recognition using 3D data, namely PointNet, capable of learning object classes from point clouds discretized as occupancy grids with uniform voxel grids in the tridimensional space. Section 2.3 describes this architecture, its data representation, and also benchmarks it on a standard 3D object classification dataset (ModelNet) to validate it.

Following that, Section 2.4 analyzes how noise and occlusion impact such 3D deep learning architecture and the importance of the data representation when dealing with such adverse conditions that commonly appear in the real world. In that study, we also propose minor changes to the architecture and the representation themselves that significantly boost accuracy with regard to the originally proposed PointNet.

At last, Section 2.5 takes all the lessons learned from the initial PointNet proposal and the extensive study to introduce a novel slice-based architecture to tackle the 3D object class recognition problem, LonchaNet, which achieved state of the art results in the aforementioned benchmark (ModelNet10).

2.2 Related Works

2.2.1 2D Object Recognition

2.2.2 RGB-D Object Recognition

2.2.3 3D Object Recognition

2.3 PointNet

The proposed system takes a point cloud of an object as an input and predicts its class label. In this regard, the proposal is twofold: a volumetric grid based on point density to estimate spatial occupancy inside each voxel, and a pure three-dimensional (3D)-CNN which is trained to predict object classes. The occupancy grid – inspired by VoxNet [16] occupancy models based on probabilistic estimates – provides a compact representation of the object’s 3D information from the point cloud. That grid is fed to the CNN architecture, which in turn computes a label for that sample, i.e., predicts the class of the object.

2.3.1 Data Representation

As we mentioned before, our proposed architecture takes a point cloud of an object as input to recognize it. However, point clouds are unstructured representations that cannot be easily handled by common CNN architectures due to the lack of a matrix-like organization. The most straightforward way to apply formal convolutions to that unstructured space is to impose a certain organization into it.

Occupancy grids are data structures which allow us to obtain a compact representation of the volumetric space. They stand between meshes or clouds, which offer rich but large amounts of information, and voxelized representations with packed but poor information. At that midpoint, occupancy grids provide considerable shape cues to perform learning, while enabling an efficient processing of that information thanks to their array-like implementation.

TODO: Talk about other approaches that make use of occupancy grids

We propose an occupancy grid inspired by the aforementioned successes but aiming to maintain a reasonable accuracy while allowing a real-time implementation. In our volumetric representation, each point of a cloud is mapped to a voxel of a fixed-size occupancy grid. Before performing that mapping, the object cloud is scaled to fit the grid. Each voxel will hold a value representing the number of points mapped to itself. At last, the values held by each cell are normalized. Figure 1 shows the proposed occupancy grid representation for a sample object.

2.3.2 Network Architecture

2.3.3 Experiments

This architecture was implemented using the Point Cloud Library (PCL) [23] which contains state-of-the-art algorithms for 3D point cloud processing and Caffe [19], a deep learning framework developed and maintained by the Berkeley Vision and Learning Center (BVLC) and an active community of contributors on GitHub 1. This BSD-licensed C++ library allows us to design, train, and deploy CNN architectures efficiently, mainly thanks to its drop-in integration of NVIDIA cuDNN [24] to take advantage of GPU acceleration.

2.3.4 Discussion**2.4 Noise and Occlusion****2.5 LonchaNet****2.6 Conclusion**

Chapter 3

Semantic Segmentation

3.1 Introduction

3.2 Related Works

3.3 The RobotriX

3.4 UnrealROX

3.5 2D-3D-SeGCN

Chapter 4

Tactile Sensing

4.1 Introduction

4.2 Related Works

4.3 TactileGCN

4.4 Conclusion

Chapter 5

Conclusion

5.1 Findings and Conclusions

5.2 Limitations

5.3 Future Work

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