Interpretation of neural networks and advanced image augmentation for visual end-to-end control of drones

Master's Thesis submitted to the

Faculty of Informatics of the *Università della Svizzera Italiana*

in partial fulfillment of the requirements for the degree of

Master of Science in Informatics

presented by

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under the supervision of

Prof. Alessandro Giusti

co-supervised by

Dr. Dario Mantegazza

February 2021

I certify that except where due acknowledgement has been given, the work presented in this thesis is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; and the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program.

Marco Ferri
Lugano, 22 February 2021

To someone

"Sometimes it is the people no one
can imagine anything of, who do
the things no one can imagine."

The Imitation Game

Abstract

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Contents

Figures

Tables

Chapter 1

Introduction

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1.1 Objective

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1.2 Outline

The thesis is composed of X chapters, whose main points are presented as follows:

- Chapter 6 summarises the previous research on the topic, evaluating the approaches adopted by the authors;
- Chapter 6 provides the background knowledge needed to properly understand the research contents;
- Chapter 6 presents the tools used for the data collection and all the additional frameworks we relied on;
- Chapter 6 thoroughly illustrates the methodology used, their benefits and limitations, also including descriptions of the kind of data used and how they are collected;
- Chapter 6 explores the analysis conducted and shows evaluation results;
- The 6 addresses the results of the experiments, concludes the thesis by discussing the implications of our findings, possible improvements and outlines future works.

Chapter 2

Chapter Title

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2.1 Robotics

2.1.1 Pose

2.2 Machine Learning

2.3 Human-drone Interaction

2.3.1 ProximityNet

2.4 Network Interpretability

2.5 Network Generalization

Chapter 3

System Description

This chapter aims to provide a generic view of our system. First, we briefly describe the existing environment, its main components and how they interact for flying and controlling the drone. Next, we list tools, software and libraries used to achieve the goal of making the drone able to fly in any other environment.

3.1 Environment

Since we mainly focus on improving the ProximityNet model described in section 2.3.1, we need to know the physical environment in which the original research has been conducted, located at the Swiss AI Lab Istituto Dalle Molle di Studi sull'Intelligenza Artificiale (IDSIA) in Lugano.

3.1.1 Parrot Bebop Drone 2

Figure 3.1: Parrot Bebop Drone 2

The entire work is built around the Parrot Bebop Drone 2 (figure 3.1), a lightweight drone (500 grams) with size of $382 \times 328 \times 89$ millimeters. A 2700 mAh swappable battery gives power to four brushless engines and dual-core processor with quad-core GPU for a maximum flight time of 25 minutes. Connectivity is provided through 2.4

GHz 802.11a/b/n/ac Wi-Fi that enables remote control via mobile app or Parrot Skycontroller (up to a distance of 2km).

The drone is equipped with many simultaneous sensor to compute drone's velocities, orientation, altitude, attitude and GPS coordinates to ensure the maximum stability during the whole flight. However, for this project we mainly care about its camera, able to shoot 14 megapixel (MP) photos and record Full HD 1080p videos at 30 frames per second (FPS). Even though the original field of view (FOV) is 180°, raw camera images pass through a software stabilization that produces 16:9 images with a horizontal FOV of 90°. The 3-axis digital stabilization technique implemented by Parrot is able to compensate for drone's pitch and roll, in order to provide correct-oriented horizontal images and stable videos regardless the drone's movements. Full specifications provided by the official Parrot Documentation [2015].

3.1.2 OptiTrack

For tracking drone's movement a motion capture (MoCap) system is required, able to record 3D coordinate of objects and people in space. The technique is widely use for motion tracking in a large variety of fields such as film making and animation, virtual reality, sport, medicine and even military. A common way to implement a MoCap systems is by using special cameras placed around the area to be tracked, able to collect optical signals from passive[1] or active markers[2] inside the area.

IDSIA adopt OptiTrack, which is producing real-time MoCap systems since 1996 and are the today world's choice for low-latency and high-precision 6 degrees of freedom (DoF) tracking for ground and aerial robotics both indoor and outdoor. Full documentation is available on the OptiTrack Website.

3.1.3 Drone Arena

At IDSIA, a dedicated room has been equipped with an OptiTrack MoCap system composed by 12 OptiTrack Prime^{x}13 infrared (IR) cameras for medium-sized areas (figure 3.3a, 1.3 MP, 240 FPS, ± 0.20 mm 3D accuracy in a 9×9 meters area with 14mm marker), to track movements of passive markers placed on the person's head facing the drone and on the drone itself. Schematic and actual representation of the arena are shown in figures 3.2 and 3.3b. Such composition is able to track a theoretical number of 18 drones inside an available area of 6×6 meters (here surrounded by a safety net), with a virtual fence of 4.8×4.8 meters which virtually constraints the total area in which the drone is allowed to fly.

[1] a passive marker reflect light

[2] an active marker emits its own light

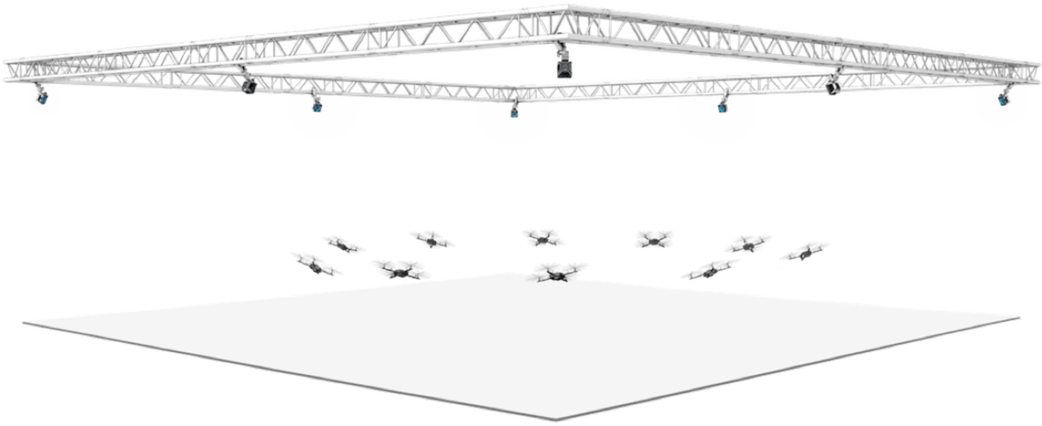
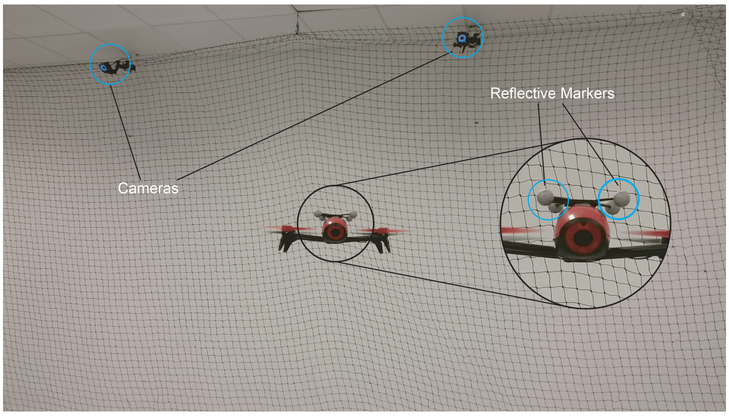


Figure 3.2: Schematic OptiTrack system with 12 OptiTrack Prime cameras

(a) Prime^{x}13 camera



(b) Drone in front of the cameras with passive markers

Figure 3.3: Drone arena at IDSIA

3.1.4 Robot Operating System (ROS)

Robot Operating System (ROS) is an open-source robotics middleware suite of software libraries and tools for building distributed and modular robot applications. It provides hardware astraction and orchestration, implementation of commonly used functionality, message-passing between processes, and package management. ROS organizes its components in graph architecture composed by nodes which communicates via a publish/subscribe mechanism, supporting a wide variety of robots also used for education. The main client library is available in C++, Python and Lisp.

Some of the most important ROS features include Standard Message Definitions, Robot Geometry and Description, Remote Procedure Calls, Diagnostics, Pose Estimation, Localization, Mapping, and Navigation. It also provides additional tools, such as Rviz (3D visualization of robots and various types of sensor data) and

Gazebo (3D indoor and outdoor multi-robot simulator, complete with dynamic and kinematic physics, and a pluggable physics engine).

ROS has grown to include a large community of active users worldwide. Historically, the majority of the users were in research labs, but increasingly we are seeing adoption in the commercial sector, particularly in industrial and service robotics.

Further documentation is available on the official ROS Website.

3.1.5 Control & Data collection

Inside the arena, the drone is controlled by a ROS script which relies on the user's pose with respect to (wrt) the drone - from now on, the *target pose* (i.e., the pose of the user seen by the drone reference frame) - to compute acceleration commands for making the drone hover in front of the person, in the direction of the head at a predefined 1.5 meters distance.

During data collection, both user's and drone's poses are computed by the OptiTrack system by using proper markers placed on the drone and on the person's head, as shown in picture 3.4. The target poses over time, mathematically computed by the script, are accurately synchronized with the video stream from the front-facing camera and saved into `rosbag` files.

These data are used to build the dataset for training a machine learning model, which should be able to infer the target pose by seeing a picture taken by the drone's camera. Figure 3.5 shows an illustration of the system from a bird-eye view.

Figure 3.4: Passive markers placed on top of drone and user's head

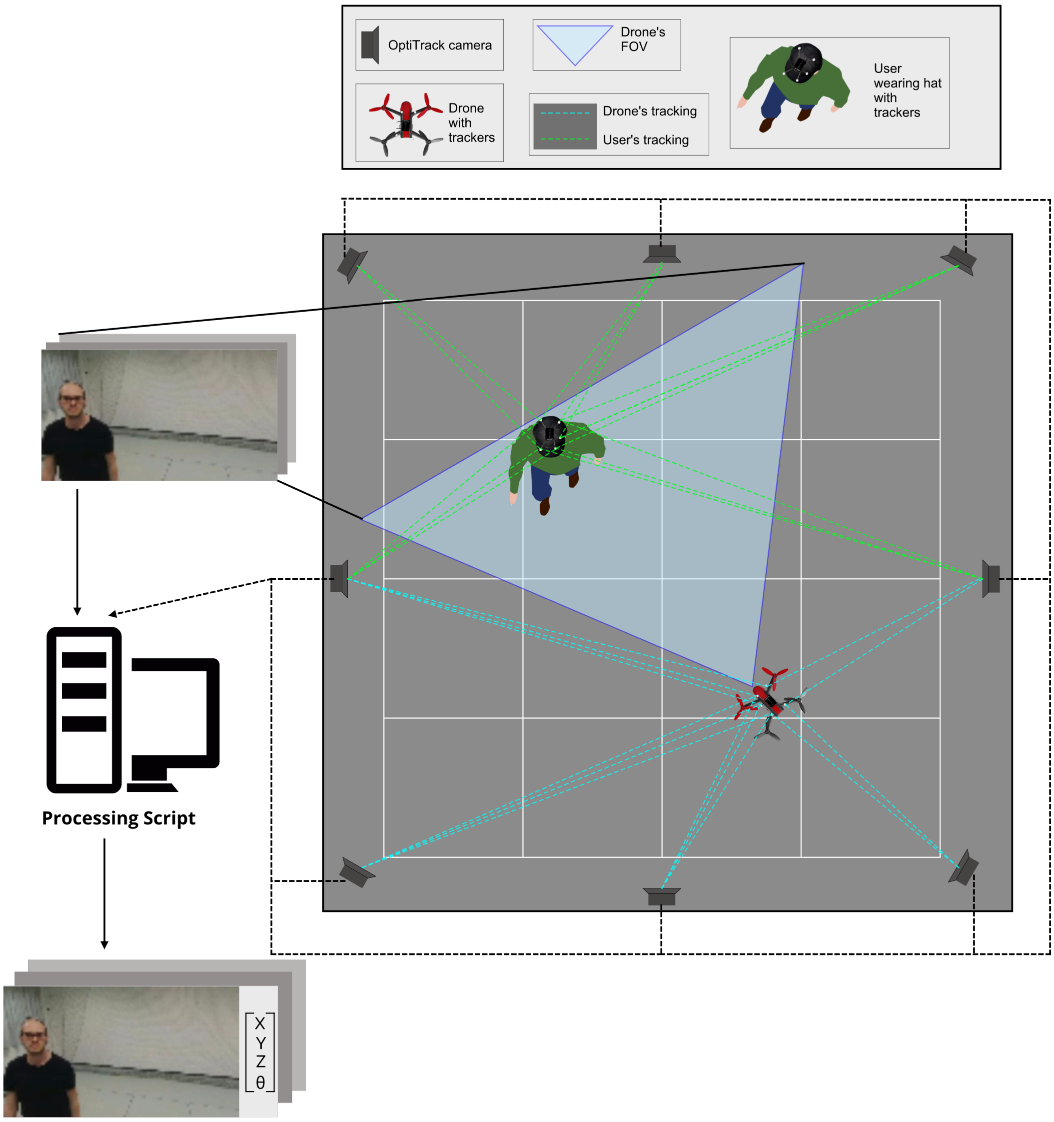


Figure 3.5: Data collection in the drone arena through OptiTrack and video stream

3.2 Development

This section presents tools and software used to conduct our research for improving the existing system from a machine learning point of view, according to the objective of the thesis.

3.2.1 Tools

The entire source code is written in Python 3. First experiments were carried out with Jupyter Notebooks via Google Colab on a GPU-accelerated runtime, while the final code is provided as classic Python scripts to be executable on a custom machine.

For debugging a Windows 10 laptop equipped with an NVIDIA GeForce GTX 950M graphic card has been used, while actual training has been performed on a dedicated Ubuntu 18.04 workstation available at IDSIA mounting four NVIDIA GeForce RTX 2080 Ti (still used for single-GPU computing, not simultaneously).

3.2.2 Frameworks

The original work from Mantegazza et al. [2019] is written in Python and based on TensorFlow 1 and Keras. These libraries have been kept, but our project uses their updated versions for ease of use. Other intensively used frameworks are listed below.

`Numpy` Largely used in the whole project for computation on arrays. Numpy is the fundamental package for scientific computing in Python. It is a Python library that provides a multidimensional array object, various derived objects (such as masked arrays and matrices), and an assortment of routines for fast operations on arrays.

`Pickle` Mainly used for saving and restoring Numpy arrays. The pickle module implements binary protocols for serializing and de-serializing a Python object structure.

`Matplotlib` First choice for building charts, visualize images or any kind of figure. Matplotlib is a comprehensive library for creating static, animated, and interactive visualizations in Python. Its `pyplot` module is inspired by MATLAB.

`OpenCV` Mainly used for efficient image and video manipulation together with Matplotlib. OpenCV is an open-source library that includes several hundreds of computer vision algorithms.

`TensorFlow 2` All the project strongly relies on TensorFlow (TF) from start to end: network interpretation, person masking, training and quantitative evaluation. Created by the Google Brain team, TensorFlow is an open source library for numerical computation and large-scale machine learning. It can be used across a range of tasks but has a particular focus on training and inference of deep neural networks. In version 2, it introduces a lot of comforts for easier development with a less steep learning curve.

`Keras` Used for defining the network architecture, training and evaluating the model. Keras is the high-level API of TensorFlow 2: an approchable, highly-productive interface for solving machine learning problems, with a focus on modern deep learning. It provides essential abstractions and building blocks for developing and shipping machine learning solutions with high iteration velocity.

`TensorBoard` Used with TensorFlow to precisely profile data generator performance for optimizing training time. TensorBoard is a tool for providing the measurements and visualizations needed during the machine learning workflow. It enables tracking experiment metrics, visualizing the model graph, and much more.

`Sklearn` Only used for automatically compute some evaluation metrics, Sklearn is a simple and efficient tools for predictive data analysis reusable in various contexts built on NumPy, SciPy, and Matplotlib.

`tf-keras-vis` Used for applying GradCAM and other interpretability techniques. Open-source library for network interpretation, available on GitHub thanks to Kubota [2020]. Derived from the original keras-vis (Google [2020]) high-level toolkit for visualizing and debugging your trained keras neural net models.

`akTwelve Mask_RCNN` Used for human detection and segmentation in background replacement. Open-source implementation of Mask R-CNN on Python 3, Keras, and TensorFlow available on GitHub thanks to Kelly [2020]. The model generates bounding boxes and segmentation masks for each instance of an object in the image. It's based on Feature Pyramid Network (FPN) and a ResNet101 backbone.

Chapter 4

Chapter Title

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Chapter 5

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Chapter 6

Chapter Title

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Chapter 7

Conclusion

This chapter presents first, in Section 7.1, our concluding thoughts and finally suggestions for possible future research lines in Section 7.2.

7.1 Final Thoughts

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7.2 Future Works

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Chapter 8

Latex features

```
ACCURACY     10-FOLD CROSS VALIDATION:    0.8290 (std dev 0.005217)
PRECISION    10-FOLD CROSS VALIDATION:    0.8371 (std dev 0.009706)
RECALL       10-FOLD CROSS VALIDATION:    0.8176 (std dev 0.008412)
F1           10-FOLD CROSS VALIDATION:    0.8273 (std dev 0.004608)
```

In this work we consider cooperative multi-agent scenarios, in which multiple robots collaborate, and possibly communicate, to achieve a common goal [**?**]. Let'try this [1]. Homogeneous Multi-Agent Systems (MAS) are composed of N interacting agents, which have the same physical structure and observation capabilities, so they can be considered to be interchangeable and cooperate to solve a given task [**??**]. This system is characterised by a state S — which can be decomposed in sets of local states for each agent and the set of possible observations O for each agent — obtained through sensors and the set of possible actions A for each agent.

- prodotti e utenti nella stessa rete, collegati attraverso le recensioni
- rete di soli prodotti, collegati tramite similarità
- rete di soli utenti, collegati tramite similarità

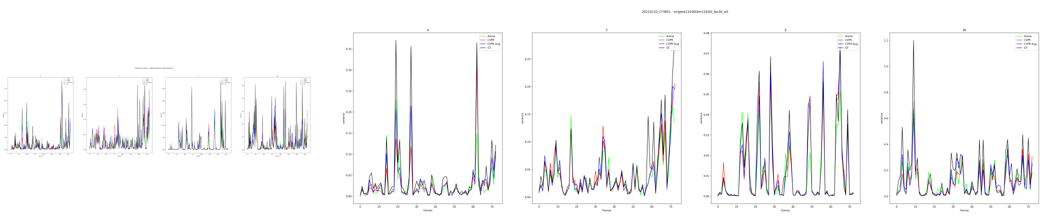

Figure 8.1: current caption

[1] this is a footnote

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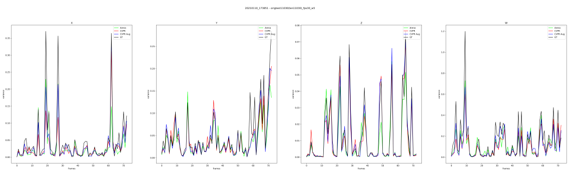

Figure 8.2: current caption [?].

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```
def tfdata_generator(files, input_size, batch_size, backgrounds,
                     bg_smoothmask, aug_prob = 0, noises = [],
                     prefetch = True, parallelize = True,
                     deterministic = False, cache = False, repeat = 1) :

    map_parallel = tf.data.experimental.AUTOTUNE if parallelize else
                                 None
    backgrounds = tf.convert_to_tensor(backgrounds) # saves time
                                 during training
    noises = tf.convert_to_tensor(noises) # saves time during
                                 training

    gen = tf.data.Dataset.from_tensor_slices(files)
    gen = gen.map(lambda filename : map_parse_input(filename,
                                 input_size), map_parallel,
                                 deterministic)

    if cache :
        gen = gen.cache()
        if not deterministic : # shuffling would destroy determinism
```

```
            gen = gen.shuffle(len(files), reshuffle_each_iteration =
                                           True)

    gen = gen.map(lambda img, mask, gt : map_replace_background(img,
                                           mask, gt, backgrounds,
                                          bg_smoothmask), map_parallel,
                                          deterministic)
    gen = gen.map(lambda img, gt : map_augmentation(img, gt,
                                          aug_prob, noises), map_parallel,
                                          deterministic)
    gen = gen.map(lambda img, gt : map_preprocessing(img, gt),
                                          map_parallel, deterministic)
    gen = gen.batch(batch_size, drop_remainder = True)
    gen = gen.repeat(repeat)

    if prefetch :
        gen = gen.prefetch(tf.data.experimental.AUTOTUNE)

    return gen
```

Listing 8.1: Protocol used by the manual controller to decide, for each robot, the message to transmit and the colour.

Table 8.1: Schema originale del dataset

Campo	Descrizione
reviewerID	ID utente
reviewerName	Nome utente
asin	ID prodotto
reviewText	Testo della recensione
summary	Titolo della recensione
helpful	Utilità della recensione
overall	Punteggio
reviewTime	Timestamp in formato string
unixReviewTime	Timestamp in formato unix

`Numpy` Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

`Keras` Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris. Nam arcu libero, nonummy eget, consectetuer id, vulputate a, magna. Donec vehicula augue eu neque. Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas. Mauris ut leo. Cras viverra metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat. Integer sapien est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus. Morbi dolor nulla, malesuada eu, pulvinar at, mollis ac, nulla. Curabitur auctor semper nulla. Donec varius orci eget risus. Duis nibh mi, congue eu, accumsan eleifend, sagittis quis, diam. Duis eget orci sit amet orci dignissim rutrum.

Appendix A

List of Acronyms

DoF degrees of freedom

FOV field of view

FPS frames per second

IDSIA Istituto Dalle Molle di Studi sull'Intelligenza Artificiale

IR infrared

MoCap motion capture

MP megapixel

ROS Robot Operating System

wrt with respect to

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