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Deep Learning Methodologies for UWB Ranging Error Compensation

Author: Simone Angarano
Supervisor: Prof. Marcello Chiaberge

Abstract. Ultra-Wideband is becoming extensively used in many kinds of robot and human positioning systems. From industrial robotic tasks to drones used for search and rescue operations, this high-accuracy technology allows to locate a target with an error of a few centimeters, outperforming other existing low-cost ranging methods like Bluetooth and Wi-Fi. This fact also lead Apple to equip the latest IPhone 11 with an UWB module specifically for precise localization applications. Unfortunately, this technology is very accurate only in Line-Of-Sight. Indeed, performances degrade significantly in Non-Line-Of-Sight scenarios, in which walls, furniture or people obstruct the direct path between the antennas. Moreover, reflections constitute another source of error, causing the receiver to detect multiple signals with different delays. The aim of this thesis is to compensate NLOS and multi-path errors and obtain a precise and reliable positioning system, that could allow to develop several service robotics applications that are now limited by unsatisfactory accuracies. Another fundamental goal is to guarantee a good scalability of the system to unseen scenarios, that is where even modern mitigation methods still fail. For this scope, a large dataset is built taking both LOS and NLOS measurements in different environments and experimenting on different types of obstacles. Then, modern deep learning methods are used to design a Convolutional Neural Network that estimates the error of the range estimates directly from raw Channel Impulse Response samples. Finally, a positioning test is conducted to verify the effectiveness of the method in a real scenario.

1. Introduction

The outstanding progress of robotics in the last two decades, aided by the increasing development of disciplines like control theory and machine learning, has led to the design of countless automated solutions for a wide variety of application fields. In particular, recent years have seen a growing interest in employing robots in everyday life contexts, pushed by the enormous innovation that this could bring in houses, offices and hospitals. Clearly, though, using moving robotic systems in uncontrolled and continuously changing environments gives rise to numerous issues. The presence of obstacles like people or objects, for example, requires the robot to have a very high confidence of the world around to travel from point to point in security. Dealing with these criticalities, the availability of a precise localization system is of paramount importance as the construction of a map is the first step for the unmanned vehicle to navigate in a complex environment. For this purpose, UWB is becoming extensively used in many kinds of applications for its high-accuracy technology, allowing to locate a target with an error of a few centimeters, and its low cost. This thesis aims at studying and compensating the errors in UWB positioning caused by NLOS conditions and reflections.

2. Proposed Approach

Differently from most of the existing literature, the present thesis investigates the possibility of performing error compensation on the single range estimates obtaining an improvement on the final position accuracy. The reason behind this choice is that a lower level method can more easily provide generalization with respect to factors like the environment and the type of obstacle. Deep learning methodologies are used to accomplish the task, as their great potentiality allows to recognize complex underlying correlations in data and to learn patterns generalizable to a wide variety of different situations. To extract the meaningful information attached to each range estimate, the model processes Channel Impulse Response (CIR) signals, that give a description of the propagation medium of the UWB radiation. In this way, the network learns to predict the measurement error and, hence, is able to refine the data. After the model has processed the range samples, a localization algorithm estimates the 3D position of the UWB tag from the corrected measurements.

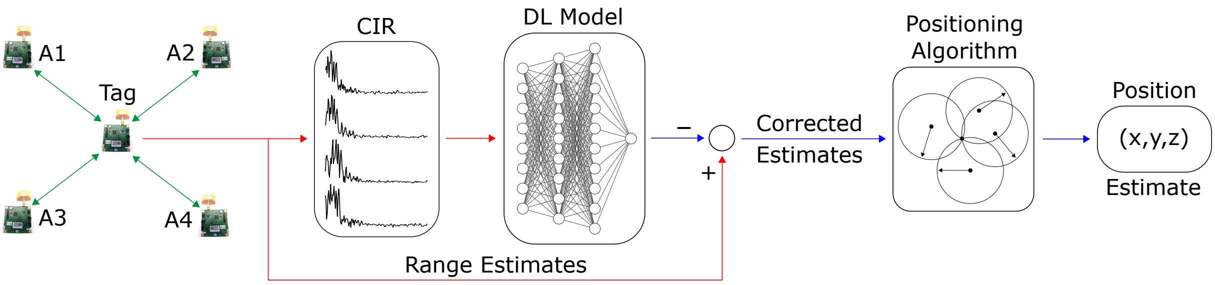

Figure 1. Scheme of the complete compensation method.

3. Experimental Workflow

To guarantee a proper training for the deep learning models and to aim at reaching the maximum generalization, a dataset of over 55 thousand range samples has been built. The measurements cover a wide variety of LOS and NLOS scenarios, as five different environments and ten different obstacles have been included. For each sample, the measurement error is computed thanks to the ground-truth provided by a laser tracker. Two deep learning models, a Multi-Layer Perceptron (MLP) and a Convolutional Neural Network (CNN) are trained and tested on the dataset to have a benchmark of the achievable accuracy. As the scope of the thesis is to verify the validity of the approach, only a modest effort is dedicated to the research of the optimal network to reach better and better results. Indeed, the experimentation shows that very good results can be found quite easily using simple models. After the validity of the method has been verified on the whole dataset, a series of tests are conducted to study the effect of different environments and obstacles on the performance of the models. The networks are trained on a specific split of data with a common condition, for example the room in which the measurements are taken or the type of object used as obstacle, and tested on the rest of the possible scenarios. In this way it is possible to state whether the approach holds a certain independency with respect to such factors. Finally, a positioning test is conducted in a typical real-time scenario using the Gauss-Newton algorithm and an Extended Kalman Filter for 3D localization. The estimation has been performed at the same time both on raw range measurements and corrected ones and the results are compared. The test has taken place in two different rooms, one already used to build the dataset and one completely new.

4. Results and Conclusions

Both the models prove the validity of the proposed idea. Using the whole dataset to feed the models, the results show a reduction of the mean absolute error of over 45%, reaching the value of 6.7cm, which is impressive considering that the Mean Absolute Error (MAE) of the LOS ranges of the dataset is 5.9cm. For what concerns environmental influence, the main cause of error are the reflections of the signal on walls and objects, and this is confirmed by the fact that the two most different settings are the outdoor and the small room, which is largely influenced by multipath components. Between similar rooms, instead, the difference in terms of performance is minimum. For obstacles, a more marked distinction can be noticed: heavy materials have a very different impact on UWB signals with respect to wood and plastic. The major problem, however, is found when a net trained on NLOS samples tries to correct LOS measurements. Nevertheless, there almost always is an improvement of the raw MAE: this means that the models are able to learn a way to compensate part of the error independently from the type of obstacle, and also that a dataset containing a sufficient number of examples for a wide variety of materials can lead to excellent results in many different scenarios. All the positioning results show an improvement in the estimation accuracy up to 65%. It is interesting to notice that a significant enhancement can be achieved even in LOS scenarios. This confirms that the shape and dimension of the environment affects the proposed method only marginally and that compensating range errors leads to an important improvement on the position estimation.

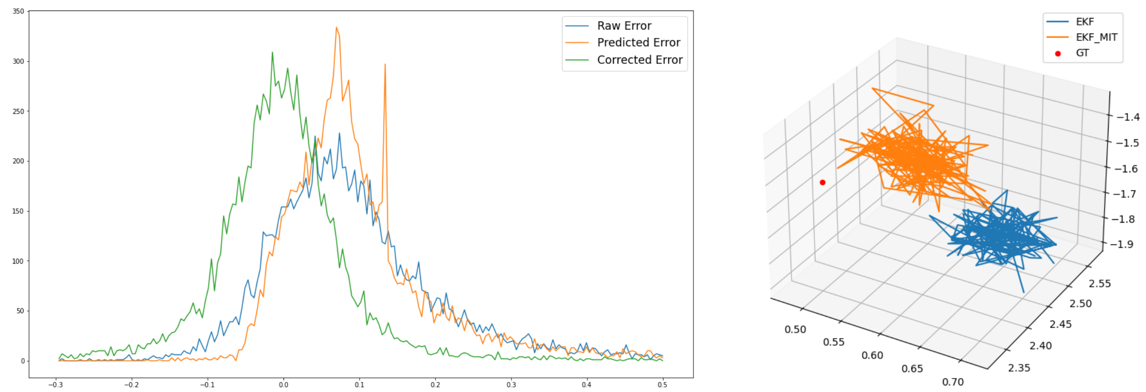

Figure 2. Statistical distribution of the ranging error (raw values, model predictions and corrected output) and 3D representation of the position estimates (raw results in blue, corrected results in orange, ground truth in red).

In conclusion, the validity of the deep learning approach has been demonstrated by the results achieved on both range and positioning correction. Moreover, a study of the effects of different factors on the accuracy has been conducted to highlight strengths and weak points of the method. A good number of future goals can be aimed, from the inclusion of new measurement scenarios in the dataset to the developing of more precise localization algorithms. Moreover, great importance resides on the possibility of implementing the compensation model and the positioning algorithm directly on the UWB sensors to perform the estimation refinement on board. For this reason, a deep analysis of the trade-off between model complexity and achieved accuracy should be conducted with particular attention to power consumption and physical dimensions. The results of this thesis, showing how very good accuracies can be achieved with simple models, pave the way to the design of an all-in-one compensated UWB positioning system.