# Relative Localization Methodology in Collaborative Robotic Environments

**Doctoral Thesis – Summary**

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The PhD thesis titled "Relative Localization Methodology in Collaborative Robotic Environments" brings contributions to a highly relevant field, the one related to the relative positioning in the context of the exploration of autonomous robots in unknown environments.

Over the last decade, this field has witnessed a strong growth due to its wide applicability: surveillance robots, search and rescue robots, underwater robots, robots for mining operations, cleaning robots, robots for farm monitoring and the benefits which they bring: cost saving over time, facilitating human activities, performing tasks that are very difficult or even impossible to carry out by a person. Thus, the problem covered by this thesis is of major interest, both in the academic and industrial spheres.

Considering that in the future autonomous robots will get more and more tasks to do in various fields, it is obvious that their localization is nowadays a topic of great relevance.

The main purpose and the result of the research activity is to propose a relative localization methodology [1], based on mathematical models, algorithms, localization methods and technologies that can be useful in exploration applications with autonomous mobile robots in unknown environments.

This methodology is validated by implementing a device to obtain the orientation and position of the robot in the navigation task, IRULT (Inter-Robot Ultrasonic Localization Turret) [2][3], which takes part of the perception module of WIT (Wireless Intelligent Terminal) within the research project: CORE-TX (COllaborative Robotic Environment – the Timisoara eXperiment) [4]. Also, the validation is extended by implementing a simulator that includes experiments covering isolated cases that may occur in practice.

**Chapter 1** of the thesis, titled "**Introduction**" begins with a brief introduction to the research conducted by the author. The chapter continues with the actuality of the thesis, the scope and the motivation that underpinned the author's research program. Later on, are presented the main objectives that the author has proposed, and at the end of the chapter is shown the structure of the thesis.

The DSPLabs laboratory projects have been an important motivation for choosing this subject. Another motivation is represented by the existing problems in the localization of autonomous robots. To highlight the existing problems in a structural way, the author of the thesis exposes the influence factors in localization: independence of fixed landmarks, dynamics of the environment, execution speed, accuracy, scalability, connectivity, energetic efficiency, cost, robustness and standardization. Also, another motivation is the large variety of applicability, including, monitoring of radioactive environments [5], traffic monitoring and routing [6], sea exploration for studying marine creatures [7][8], missions in space to research and discover unexplored areas [9], smart robotic appliances such as an intelligent vacuum cleaners [10] or intelligent wheelchair robots [11][12], robots for food distribution or shopping companion robots [13]; these are just a few examples where localization plays an important role.

The objectives of the thesis are as follows:

(1) Analyzing and structuring existing solutions, highlighting the most important existing technologies and technologies.

(2) Identifying the influence factors and existing problems in localization of mobile robots.

(3) Developing methods for computing distance between two robots using technology based on mechanical signals.

(4) Proposing a hardware system for mobile robots that provide localization facilities based on methods of distance computing.

(5) Developing a localization methodology applicable for a wide range of systems, taking the CORE-TX system as an example.

(6) Conceiving and defining a mathematical localization model based on cooperation and multilateral localization and validating it.

(7) Defining some rules by which to keep the localization confidence of mobile robots at the highest level.

(8) Illustrating the methodology on a concrete case study.

(9) Elaborating of a localization algorithm with superior confidence for distributed processing systems.

In **Chapter 2** titled **„Localization, current approaches"** A classification of localization systems is presented. As a first categorization, localization systems can be grouped in "global" and "local". The basic purpose of this chapter is to define the classification terms that will be used in the other chapters. For each defined classification category, at least one example of an existing localization system is presented. Existing localization solutions may have features belonging to one or more of the categories defined by the author:

CAT I – global localization systems

CAT II – local localization systems with fixed active landmarks

CAT III – local localization systems with fixed passive landmarks

CAT IV – local localization systems with mobile landmarks

CAT V – local localization systems without landmarks

This chapter also presents some representative localization techniques as well as the specific technologies related thereto. At the end of the chapter, the author shows the factors that influence the localization systems on which the problems and proposed solutions are structured. The problems and proposals are shown as follows:

1) independence of fixed landmarks:

Problem: The most common localization systems for autonomous robots are built to be dependent on fixed landmarks. Here we can refer to the localization systems based on categories CAT I, CAT II and CAT III.

Proposal: If independence from fixed landmarks is desired, then the following categories are more appropriate: CAT IV and CAT V. In this thesis the author proposes a localization system belonging to the CAT IV category. The author also proposes a hybrid system combining the CAT II and CAT IV categories.

2) dynamics of the environment:

Problem: If the localization system is used in an environment where changes occur, such as, the number of people, the presence of different objects (example: furniture), localization is much more difficult. Certain localization system of CAT III may have difficulty in this regard. Also, localization systems of CAT II which use methods such as fingerprinting (2.4.1), have big problems when the environment becomes dynamic.

Proposal: For applications where the environment is dynamic, any category would be appropriate except category III. Approaches such as fingerprinting should also be avoided. In this thesis the author proposes a metric approach in which mobile robots preserve their positions through the so-called "localization webs". The advantage of this approach, presented in Chapter 4, is that the positioning of these webs is quite flexible, so the system could also work in dynamic environments.

3) execution speed:

Problem: In localization systems, depending on the applied algorithm, calculations are repeated to achieve a better accuracy. This increases the time in position calculation.

Proposal: It is suggested to decompose the algorithm into multiple threads of execution and processes, so that, the calculation is transmitted to a central node (server/cloud) where it will be executed on multiple processors. In this thesis, this is shown to be done with the help of the central node, BRAIN (Background Robotic Activity Induction Node), defined in the Core-TX research project.

4) accuracy:

Problem: The localization accuracy depends directly on the sensitivity of the sensors and how the sensor information is used. Also, for example, computational errors in distance measurements, derived from reflections, refractions and diffractions, can lead to large errors in localization.

Proposal: To obtain a precise location, complex signal processing techniques are needed to identify the direct line of sight (if exists) and to minimize / eliminate the multiple-path signal effects. For example, the technologies presented in 2.4.2 CSS and 2.4.3 UWB are more robust in multiple paths and noise, compared to the technology presented in 2.4.1 WLAN. In this thesis, the application of robust technologies, such as CSS or UWB in the form of CAT II localization system are proposed to compensate the propagation errors of CAT IV localization system also presented in this thesis. Chapter 6 shows how the combination of the two categories reach a better localization accuracy.

5) scalability:

Problem: In a network of robots, their number may be in the order of hundreds or thousands, which increases the complexity of the localization protocol. This problem is specific to the CAT IV category.

Proposal: It is solved by introducing the *bases*. At the *base* level, it is suggested that the protocol be decomposed into multiple threads of execution and processes, so that the localization is managed by a central node (server / cloud) where the protocol runs on multiple processors. As the “execution speed”, in this thesis, scalability is achieved with the help of the central node, BRAIN.

6) connectivity:

Problem: The density of the robots must be large enough to avoid losing connections, but at the same time, a high density makes communication more difficult due to the wireless environment collision avoidance feature. This issue is specific to category CAT IV.

Proposal: Three areas of visibility are proposed: the green area for computing the distance or angle between two mobile robots, yellow area for communication between two robots and red area where the communication is not possible. These definitions are part of the proposed methodology set out in Chapter 4. Also, the connectivity is managed centrally (server / cloud) according to the mobility rules outlined in Chapter 6.

7) energetic efficiency:

Problem: The sophisticated algorithms could bring considerable consumption for the autonomous mobile robot.

Proposal: Decomposing the complex algorithms into multiple threads of execution and processes, so that the computations can be performed in a central node (server/cloud) where algorithms run on multiple processors. As in the case of “execution speed” and “scalability”, complex algorithms that lead to a significant energy consumption, are also to be executed with the help of the central node, BRAIN.

8) the cost:

Problem: The price of additional modules that bring a major improvement in localization is very high.

Proposal: simple and low-cost hardware modules, which calculate the distances between two modules of the same type using ultrasonic waves at millimeters scale accuracy. The module is presented in Chapter 3.

9) robustness:

Problem: The situation when certain sensors fail, measurements fail, or a mobile robot becomes completely dysfunctional should be analyzed.

Proposal: Chapter 3 proposes a hardware module with two functional sensors, but with a double role, each sensor could cover the case where the other sensor would fail. Thus, with some constraints, the hardware module could be functional, if maximum one sensor fails. Also, in Chapter 3, two distance computation methods are presented: unidirectional and bidirectional. Therefore, if the bidirectional method fails, unidirectional method could be used. The methodology shown in Chapter 4 defines a *web* that is composed of at least two robots. To increase robustness, the number of mobile robots in a *web* should be increased.

10) standardization:

Problem: Currently a standard which governs localization research in the interior of buildings does not exist[14].

Proposal: Regardless of standards, this thesis proposes a relative localization methodology that can be useful in designing exploration solutions of autonomous robots in unknown environments.

**Third Chapter**, "**The proposed hardware localization system**" presents a new hardware concept for the orientation and localization of mobile robots in two dimensions, called IRULT (Inter-Robot Ultrasonic Localization Turret). Some other existing hardware localization modules are also presented. In the second part of the chapter, the author describes a series of methods that underlie the proposed orientation and localization model of mobile robots. One of these methods is based on the alignment algorithm [15][16]. The alignment is an essential step in the orientation and localization model of mobile robots representing the starting point of the model. At the end of the chapter, two distance computation methods and related experimental results are described. These results are exposed to be referenced and used in the next chapters of the thesis.

Experimental results show that although the MTDOA (Modified Time Difference of Arrival) method [17] generates relatively high absolute errors, the average value is closer to the actual distance and has a linear evolution, these being obtained after the appropriate calibration adjustments. Moreover, the relative maximum errors tend to decrease with the measured distance. This is an indication that the delays caused by the Xbee module operation predominantly contribute to influencing experimental results. An improvement of this technique could be to perform measurements in both directions for a position of the robot, and if the results differ significantly, the procedure should be resumed.

On the other hand, CTOF (Combined Time of Flight) method [17] has proved to be much better. After the necessary calibration steps, its measurement characteristics are linear, and the measurement results are much closer to the real distance. This demonstrates the independence of this technique from the random delays introduced by the Xbee communication modules.

**Chapter 4** called **„Proposed localization methodology"** is an original chapter in which the author presents the localization methodology based on three levels: 1-PREDICTION, 2-COOPERATION and 3-CENTRALIZATION. The three levels are further detailed in Chapters 5 and 6. Also, in this chapter the notions underlying the proposed methodology, from which can be highlighted  are presented: basic concepts, angle measurement, system initialization, LOAD method and bilateral localization. Also, an extensive set of experiments from a case study executed in DSPLabs is presented to evaluate the proposed localization methodology. After several rounds of experimentations, the author notes that even more sets of experiments need to be performed through simulation to include as many of the isolated cases as possible, cases that can occur in practice.

Experiments were done using only two IRULT modules. The robots did not move, they were static. Real distance measurements were made using a tape measure  The IRULT modules were able to perform alignment and distance computation. As output information, using the Xbee interface, the IRULT module was able to provide the distance measured, the execution time of a distance measurement, and the alignment time. All the data has been accumulated and added to a spreadsheet, including repeated measurements for different distances. The data was processed manually, and the positioning results were determined from the calculations made in the spreadsheet. Therefore, the time for this study has increased significantly.

The experiments were not automated for two reasons: the necessary hardware modules were not available, and the localization functionality was desired to be tested separately, thus eliminating locating errors that could have come from sources other than the IRULT module. Therefore, the localization errors presented in this chapter, obtained by the experiment, only include errors from the distance measurement module, and do not contain other sources of errors.

The purpose of this research was to isolate the rest of the components of the CORE-TX system and the attention to be placed on the IRULT module and also to find good ways to filter out errors acquired by the distance measurement. Therefore, considering the errors that the IRULT module can generate, the author of the thesis developed a simulator in which he implemented the mathematical localization model. The simulator has as input the absolute error of distance measurement and can also generate positioning of the worst case, which in practice would be difficult to obtain or even harder to reproduce, because there are rare cases that have a very low probability of occurrence. Consequently, to obtain correct validation, the author of the thesis uses the simulation environment to cover all isolated cases that may occur in practice. The necessary simulations have been made and are outlined in chapters 5 and 6.

In **Chapter 5** of the thesis titled „**Applying the relative localization methodology for the CORE-TX perception and operation layer”** initially it is highlighted the first level, namely the PREDICTION, of the proposed relative localization methodology. At this level, each mobile robot self-localizes based on its own mobility and navigation resources through local processing. The method proposed by the author is based on the “dead reckoning” concept. This is a process of subordination to the following two levels of localization that are further presented. The second level (COOPERATION), which is further addressed in this chapter, is based on the multilateral localization method. Consequently, the author presents existing techniques and methods that refer to multilateral localization as well as the originally proposed mathematical model, based on the ILS (Iterative Least Squares) method. Furthermore, there are presented the forming rules for *webs* that reduce the amplitude of the error propagation. To validate the mathematical model, the author relies on the distance computations described in Chapter 3 and performs multiple error propagation simulations in the worst-case scenarios, the results of which are presented Also, here is presented the SiMuLoC simulator developed by the author for the model validation, as well as an example of an application that highlights the way in which the proposed mathematical model can be used.

The proposed, generalized mathematical model offers the ability to locate a *web* in relation to another, regardless of the number of robots that are part of the *webs*. It should be noted that localization by COOPERATION is done sequentially from *web* to *web*, so for a *web* to be localized it is only dependent on the reference *web*. This makes it possible to implement the mathematical model at WIT level. The advantage of this idea is that the localization system at the COOPERATION level can also be functional when, for various reasons, communication with the BRAIN entity is lost.

To validate the model, Monte Carlo simulations have been employed, because in practice, sequential propagation localization errors are very difficult to reproduce. When the noise distribution for distance measurement cannot be modeled, the only thing that can be done is to find the maximum and minimum distribution range. With such a noise, finding the worst cases in practice is impossible. Therefore, by applying the Monte Carlo method in simulations, it is possible to evaluate the model quickly and correctly. The simulations in the SiMuLoC simulator take this into account. This is why some issues known in the literature(such as the issue of local and global minima highlighted by Seong Yun Cho in the paper [18]) have also been reproduced. In the case of the present methodology, these problems are solved by using the forming rules for *webs* and by calling to the position information from a lower level, such as the LOAD method or localization level I (PREDICTION).

In the present approach, it was considered that random noise in the case of distance measurements can be decomposed into two parts. The first part has Gaussian distribution and the second cannot be modeled. The Gaussian distribution is resolved at IRULT module by repetitive measurements, for example by applying Kalman filter, and non-Gaussian distribution cannot be solved but must be sequentially quantified from *web* in *web*. This can be done by using the SiMuLoC simulator. By applying the various forming rules for the *webs*, highlighted in subchapter 5.7, the quantification of propagation errors is changing. That is why the methodology proposes a set of rules by which the localization confidence increases.

**Chapter 6**, „**Applying the relative localization methodology for the CORE-TX control and supervision layer**” presents the third level (CENTRALIZATION) of the proposed localization methodology, level that includes an algorithm for distributed processing systems. The BPF (Backtracking Particle Filter) proposed algorithm [19], with an original localization technique, is a "particle filter" algorithm in a form of "backtracking" and which is based on the Las Vegas probability algorithms. Because experiments in practice exposed in Chapter 4 cover a relatively isolated context, to validate the proposed methodology, the author executes several sets of simulation experiments to include as many of the isolated cases which can occur in practice. By analyzing the experimental results and introducing the "base" concept with the role of resetting the propagation errors in localization, it is shown that the proposed relative localization methodology is applicable in the context of exploring unknown environments by autonomous robots.

Usually in the literature we find localization systems for mobile robots that use the following approaches (or variations of them): SLAM, Kalman Filter, ILS or particle filters based on the Monte Carlo method. Each approach has a specific problem to be applied for exploration applications in unknown environments. For example, with the SLAM approach, it is not possible to reconstruct the location in the environment if the environment is dynamic. The Kalman Filter approach needs a sensor model, and the behavior of sensors in practice is difficult to model. The ILS approach loses accuracy when it calculates the residual value, and the errors accumulate ad-hoc. Particle filters through existing approaches require a map, instead when exploring an unknown environment, the map does not exist.

In this chapter a new concept in the localization field was discussed. The idea came after analyzing existing approaches. There was a need for a method to keep the measurement and estimation history in such a way that the correct solution is found by repetitive estimates and validations. Appealing to BPF method presented in this chapter, do not lose so much in accuracy as ILS lose accuracy in calculating the residual value. Instead, the BPF method requires a lot of computing resources. Ten years ago, or more, it was harder to imagine such a concept because of the lack of computing resources or unbearable huge costs. Today, when the notion of "cloud computing" is put into practice, new ideas are being made accessible. For example, the BRAIN entity can be seen as a cloud-based software solution. The BPF algorithm presented in this chapter has been built for the CENTRALIZATION level based on the BRAIN entity, the entity that can be represented as a set of computing services in the cloud.

The BPF algorithm is a "particle filter" algorithm but is very different from the particle filter approach found in the literature simply because it does not require a map. Moreover, the particle filters in the literature are based on the Monte Carlo model, while the BPF algorithm is based on the Las Vegas model.

Several experiments were performed in the simulator using the BPF algorithm. From the results we can see that the BPF method has better accuracy than the ILS method. It was found that data fusion is relevant to increase the localization confidence. A data fusion for the ILS method is not excluded, but it is more difficult to implement. The localization solution by building *bases* for the problem of applications with mobile robots that explore unknown environments whether the route is short or very long was also proposed

In **Chapter 7**, entitled **„Conclusions and perspectives"**, the author presents the conclusions of the scientific research carried out, highlighting the original contributions and outlining some of the future research directions.

Among the original contributions, claimed by the author, several can be mentioned:

- Identification of the most significant examples of applications in the field of autonomous robots for which the proposed methodology can be applied.
- Identification of the factors that influence the localization of mobile robots, meaningful for applications with autonomous mobile robots in unknown environments.
- Classification of the localization systems in 5 categories and exemplification of the categories.
- Analyzation of the localization problems according to the identified influence factors and proposal of related solutions.
- Identification of the most significant modules in the field of autonomous robots using ultrasonic signal technology and identifying their issues.
- Proposal and implementation of the IRULT module based on ultrasonic signals to measure distance relative to other IRULT modules and having a common set of requirements for the target robotic system, namely CORE-TX. The IRULT module has been patented. After the patent application was filed, this activity was also published in a Thomson Reuters indexed conference article.
- Development of an alignment algorithm for two turrets that are equipped with an IRULT module. This activity has been published in a Thomson Reuters indexed conference article and, in a book-chapter, published abroad.
- Development of the MTDOA and CTOF methods for computing the distance between two IRULT modules. This activity was published in a journal indexed by Thomson Reuters.
- Proposal of a three-level localization methodology: PREDICTION, COOPERATION and CENTRALIZATION.
- Definition of basic concepts in the methodology. Partially, the concepts were published in a Thomson Reuters indexed conference article.
- Elaboration of the LOAD orientation and localization method.
- Elaboration of the bilateral localization method.
- Elaboration of the localization mathematical model based on cooperation and multilateral localization.
- Development of the SiMuLoC simulator to validate the mathematical model.
- Definition of some forming rules for the *webs*.

- Illustration of the proposed methodology on a concrete case study. This activity was published in a Thomson Reuters indexed conference article.
- Elaboration of the BPF algorithm, with superior confidence, for distributed processing systems.
- Development of the Simon-TX simulator for testing the BPF algorithm and validating the methodology.
- Expansion of the BPF algorithm for relative localization based on angle and distance measurement between robots.
- Expansion of the algorithm for relative localization by building the *bases*.

The claimed elements by the author as original contributions were capitalized through 5 ISI-indexed publications, an ISI-indexed patent and a book chapter published abroad.

At the end of the chapter, the author synthesizes in a pertinent manner the perspectives for further development of the undertaken research.

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