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Extended summary

Localization and Navigation of Autonomous Systems in Complex Scenarios

Curriculum: Ingegneria Informatica, Gestionale e dell'Automazione

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Abstract. Autonomous systems represent a promising evolving area, in particular with respect to research in artificial and embedded systems. Many solutions of autonomous systems focused on solving a very specific problem are available, but the majority of these solutions, however, is proprietary. In order to become competitive in a highly dynamic market it is necessary to fill some gaps that currently slow down the diffusion of autonomous systems: The lack of platforms for the integration of components from various technology suppliers, the absence of a framework of methodologies are just some of the obstacles to overcome. In this context, the European Project R3-COP, aims to advance over the state of the art providing a contribution in both perspectives: Technology and Methodology. This Thesis has been developed in the context of the R3-COP Project, in order to overcome some of the addressed problems, and provides a contribution in both directions: Technology and Methodology. Concerning the technology, the developed localization algorithms, demonstrate the ability to leverage the latest technologies radio belonging to the IEEE 802.15.4a Standard in indoor localization. The proposed algorithm allows to model the bias of ranging data considering also the faults in the measurements in order to have a more reliable position estimation when ranging data are not available. The UWB ranging measurements allow to reduce the errors of inertial sensors due to the limited performance of MEMS accelerometers and MEMS gyros. The obtained results show that an accuracy of 15 cm can be achieved.

Concerning the methodology, the second part of this Thesis presents a 3D Simulation Environment for the prototyping and validation of cooperative tasks for unmanned systems, as part of the framework of methodologies addressed by the R3-COP project. The proposed Framework, provides also the possibility to convert the control software from Simulated Scenario into real application using MatLab/Simulink.

Keywords. UAV, Extended Kalman Filter, UWB, Inertial Navigation, Simulation

R3-COP Logo

1 Problem Statement

This Thesis provides a contribution in both direction of the R3-COP project, Technology and Methodology, and therefore the State of Art survey is divided in two distinct parts. The first part provides an analysis of the current state of the art in Localization Technologies and Algorithms for Autonomous Systems. In the second part a review of the current Software Systems for Robotic Simulations is carried out.

1.1 Localization Technologies and Algorithms for Autonomous Systems

Indoor and outdoor localization of mobile robots is very attractive in many application. In last few years, Unmanned Aerial Vehicles (UAVs) have attracted attention in different fields. They are able to perform tasks in hostile environments were access to humans is impossible or dangerous. Precision localization and navigation for these vehicles is a critical aspect that needs to be deeply analyzed.
In outdoor environments, UAV can localize itself exploiting different space-based satellite navigation systems, such as Global Positioning System (GPS). But the precision of satellite navigation systems is very limited, especially in civilian applications. Although this is not as good as can be achieved using high frequency radar, it may still be adequate for some applications [1].
In indoor environments, Wireless networks can be successfully used not only for communication between devices but also for localization. The main problems that affect range measurements using wireless networks consists in multipath and non-line-of-sight (NLOS) measurements. As example, localization based on Received Signal Strength (RSSI) could provide very poor localization informations, especially in cluttered environments.
The recent standard IEEE 802.15.4a specifies two additional physical layers (PHYs) for communication and localization: a PHY using ultra-wideband (UWB) and a PHY using chirp spread spectrum (CSS) both with a precision time-based ranging capability [2,3,4,5,6,7].
In particular, UWB is characterized by:

- High immunity to multipath effect;
- Very low power consumption;
- Capacity to penetrate obstacles (at lowest frequencies);
- Very low probability to be detected and intercepted;
- Low interference to existing wireless systems.

These characteristics make the UWB very appreciable in the developments of localization systems especially in indoor environments or when a high precision in position estimation is required.
In real scenarios, very often the precision provided by the only ranging sensors are not enough. In order to improve the accuracy, different methods based on fusion between different kind of source of data, have been developed.
The basic idea of the Sensor Fusion applied to the problem of localization is to provide an estimation of the position with an accuracy greater respect to the accuracy reachable by the various devices used individually.
For the realization of sensor fusion several techniques are available, many of which are based on a probabilistic representation of the information.

In the development of localization algorithms, ranging data are typically fused with information provided by inertial sensors.
In recent years, inertial sensors based on MEMS (MEMS IMU) have found use in many areas, mainly due to the their low cost and small size [8]. But, generally low-cost sensors are characterized also by poor performance. The most important problems of a MEMS IMU are [9]:

- Bias
- Scale factor
- Non-ortogonality
- Temperature Drift

Therefore, in order to provide an effective improvement of performances in Sensor Fusion algorithms, it is necessary to analyze in detail the behavior of such sensors and implement appropriate calibration procedures, both under static and dynamic conditions.
In this context, the proposed solutions aim to provide a genuine contribution on the development of robust sensor fusion algorithms for indoor/outdoor localization and navigation of autonomous systems exploiting the advantages of IEEE 802.15.4a technologies throughout:

- The investigation of the IEEE 802.15.4a technologies, Ultra Wide Band and Chirp Spread Spectrum, in the context of Robot Localization especially in indoor environments where the GPS signal is typically not available;
- Integration of MEMS Inertial Sensors and Cameras with UWB for a robust localization throughout Sensor Fusion Algorithms.

1.2 Software Systems for Robotic Simulations

Given the complexity of control laws that regulate the dynamics of mobile robots, and the difficulty of designing robust control systems, a very good simulation platform is often necessary.
Simulation activities are essential by making it possible to study and compare different approaches in solving a particular problem, providing not only a drastic reduction in development time but also in costs. Matlab/Simulink is an excellent choice for rapid prototyping of control systems. However, in the Simulink environment the mathematical model of the system under simulation is required. These mathematical models are in some cases too difficult to manage or not available at all. Moreover, it is difficult to model mathematically complex robot behaviors in realistic environments, as in the case of cooperative tasks. For such situations a large number of three-dimensional simulators has been developed:

- Player/Stage Gazebo [10]:
- FlightGear [11] :
- Microsoft Robotics Developer Studio [12]
- SimplySim SimplyCube [13] :
- X-Plane : X-Plane [14]

Among all the solutions outlined above, the SimplySim provides good opportunities and it can be programmed using the language of the framework .NET. In this way, it is possible to interface it with Microsoft Robotics Developer Studio and other platforms. Further it includes a full suite of tools for the realization not only of three-dimensional models of robots (also in terms of physical characteristics) but also for the realization of complete three-

dimensional scenes. This makes it quite interesting for the creation of highly realistic simulation systems. The developed Simulation Environment combines the high realism of the simulations carried out in a three-dimensional virtual environment with the easiness of Simulink for fast prototyping of control systems.
The proposed extends our previous work [15] [16] that was based on modularity and stratification in different specialized layers; the limitation was the missing of a physical engine and an advanced 3D visualization interface.

2 Research Activities

This Thesis has been developed in the context of the R3-COP Project, in order to overcome some of the addressed problems by the Project, and provides a contribution in both directions: Technology and Methodology.
In particular the work carried out and presented in this Thesis aims to provide a genuine contribution on sensor fusion algorithms for indoor/outdoor localization and navigation of autonomous systems and an advance in validation and test methods for autonomous systems, designing a 3D Simulation Environment for the prototyping and validation of cooperative tasks for unmanned systems.
Going more in details, the activities carried out in this Thesis are:

- The investigation of the IEEE 802.15.4a technologies, UWB (Ultra Wide Band) and CSS (Chirp Spread Spectrum), in the context of Robot Localization especially in indoor environments where the GPS signal is typically not available;
- Integration of MEMS Inertial Sensors and Cameras with Ranging Sensor for a robust localization throughout Sensor Fusion Algorithms;
- Development of a 3D Simulation Environment for testing and validating the developed algorithms with regards to Localization and Navigation tasks.
- Testing of Control and Localization Algorithms using the developed Simulation Environment: Some example of use of the developed Simulation Environment, such as formation control of many UAVs using Networked Decentralized Model Predictive Control, and mission management using Finite State Machines are proposed and explained.

The first part of the Thesis provides a complete overview of the work carried out in the Localization of Autonomous Systems. After a detailed analysis of the most important types of MEMS Inertial Sensors, with particular reference to MEMS gyroscope and accelerometer the primary source for Inertial Navigation Systems are analyzed. MEMS Inertial Sensors are becoming even more attractive in Robotics fields, thanks especially to their low-cost small dimensions even if they are characterized also by poor performance that need to be managed in order to get these devices reliable. Therefore, the most important source of error of MEMS Inertial Sensors are investigated. The next activity consisted in providing an overview of the Ranging Techniques in Anchor Based Localization System and the Ultra-Wide Band Technology for localization. This analysis, in conjunction with the calibration routines for MEMS Sensors, provides all the necessary knowledge base for the developed Localization Algorithms.

Fig, 1 – Unmanned Ground Vehicle equipped with CSS Ranging device

The proposed localization algorithms exploits both Physical layers of IEEE 802.15.4a standard: CSS and UWB. The high precision of UWB has been integrated with inertial measurements to provide a reliable localization of a mini-UAV in indoor environments. The CSS has been evaluated for the localization of a Unmanned Ground Vehicles (see Figure 1).

The second part of this Thesis deals with a detailed analysis of the developed 3D Simulation Environment.
This framework, based on the nVidia PhysX physical Engines provides also an interface with the MatLab/Simulink Environment.
The Simulation Environment is then used for testing different cooperative scenarios like Navigation of many UAVs in formation using Networked Decentralized Model Predictive Control.
Thanks to its interface with MatLab and Simulink, the Framework have been also tested and used by other R3-COP partners for the development of Mission Management Systems based on Finite State Machines, described in the last part of this Chapter. The possibility to interface the virtual environment with MatLab/Simulink, to develop custom mobile robots specifying physical properties, to simulate different kinds of sensors, make the developed simulator an interesting tool especially in the development of cooperative robotic systems.

3 Main results

A Localization Algorithms based on IEEE 802.145.4a Chirp Spread Spectrum (CSS) technology for the localization of an Unmanned Ground Vehicle has been developed. The algorithm is able to manage faults on measurements isolating the corrupted data without shutting down the localization system. The Nanotron RTLS Kit provides a reliable system for Ranging especially in outdoor environments using a proprietary ranging technology called Symmetrical Double-Sided Two Way Ranging (SDS-TWR). This technique tries to overtake the limitations of the classical Received Signal Strength Indication (RSSI) (e.g., Wi-fi mapping) that does not ensure good performance especially in structured environments. The set of these devices allows to create a Wireless Sensor Network (WSN) that is suitable for cooperative tasks where the data link is fundamental to share data and support the relative localization.
The management of fault measurements allows also to reduce the errors on ranging when there is not Line of Sight between the anchors and the tag, in which the performances of the system decreases.
However, the obtained results put in evidence the necessity of further ranging data to obtain centimetric accuracy in precision of localization that actually is rated to 1m, especially in indoor environments.
The UWB-based Localization Algorithm based on the UbiSense UltraWide Band System provided good performances in indoor environments (see Figure 2).
The Ultra Wide Band is a promising choice in the development of localizations systems, thank especially to its resolution and immunity to multi-path.
The proposed solution allows to use a low-cost Inertial Measurement Unit (IMU) in the prediction step and the integration of vision-odometry for the detection of markers nearness the touchdown area. The ranging measurements allow to reduce the errors of inertial sensors due to the limited performance of MEMS accelerometers and MEMS gyros. The obtained results show that an accuracy of 15 cm can be achieved.
However, a drawback of the UbiSense UltraWide Band System in Author's opinion concerns the calibration routine of the system that need to be accurately carried out in order to have the best performance. In particular, the use of a Laser pointer or a Total Station to estimate the position of the anchors with a millimetric resolution is strongly recommended to calibrate the UbiSense UWB System.
For both of the proposed version of the Kalman Filter, the calibration procedure for MEMS is a critical aspect that needs to be carried out in order to improve the a priori state estimation. The obtained results, have been published in [17,18,19].

In the second part of this Thesis, a modular framework for fast prototyping of cooperative autonomous was presented. A non linear MPC strategy to evaluate the performances of the framework has been considered. Furthermore, the Simulator has been used also for testing localization algorithms for UAV and UGV. The modularity of this framework allows to quickly develop new modules without major changes of the already developed code. In addition it allows gray-box development of control systems and the ability to perform highly realistic simulations based on the most important physics engines currently available (Newton, PhysX, and so on). The virtual environment can be enhanced simply by integrating the three-dimensional models of objects.
Development of control systems directly in Matlab/Simulink will provide the ability to generate code that can be downloaded directly on the hardware with tools like Real-Time

Workshop. Thanks to the socket connection, based on UDP protocol (see Figure 3), it is also possible to distribute the computational load across multiple computers on a network by providing an architecture formed by a computer in which the simulator runs and n computers with each one of them specialized for controlling of a modeled dynamic system. The obtained results have been published in [20,21,22].

Fig. 2 – Hardware architecture for the localization of a Mini-UAV using the UbiSense UWB Real Time Localization System

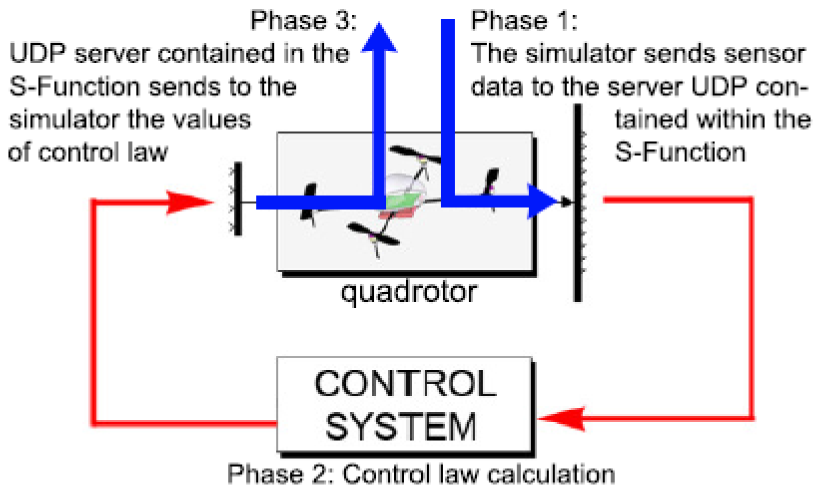

Figure 3 - Data flow between simulator and Simulink control system

4 Conclusion and Future works

In the development of localization algorithms, the Ultra Wide Band is a promising choice, thanks especially to its resolution and immunity to multi-path. However, as defined by the ETSI and FCC regulation, the power emitted by UWB is very low in order to not interfere

with other types of radio system. This of course produces a reduction of the area covered by the UWB signal. Other than increment the number of UWB anchors, the Localization algorithms could be improved considering other source of information, such as vision sensors (vision odometry). Therefore, future works could be steered to extend the set of sensors integrating visual information based on high-definition camera and to optimize the code to improve the overall performances.
In particular for the UAVs, using embedded platform with a dedicated GPU to exploit the high-parallelism of the GPU in order to make possible the video elaboration on-board avoiding delays that might occurs when video stream need to be transferred to a remote PC for the elaboration.
Concerning the second part of this Thesis, the developed Simulation Environment demonstrated to be useful n the development and testing of control system for cooperative scenarios. Future work in this field, could be steered to improve the quality of the simulation by providing the ability to model sensors that allow a higher degree of realism. This will make it possible to test new types of control algorithms based on a probabilistic representation of information.

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