

# Chapter 1

## Introduction

### 1.1 Context

Localisation and tracking of moving agents is a task that is at the centre of interest of many researchers in robotics. Indoor localisation applications are often concerned with location awareness. Such systems are able to provide location specific information, for example at exhibitions where audio information about the exhibits may be provided dependent on the visitors' position. Another important application for indoor localisation is to improve human-robot interaction, for example in hospitals. Outdoor localisation is often found in the area of asset tracking and surveillance. Systems for outdoor localisation often have absolute position information available through the use of Global Positioning System (GPS). Under certain circumstances, such as shadowing of GPS satellites or due to multipath effects, the GPS position information is not of the desired quality and sometimes not available at all.

This thesis deals with localisation and tracking of moving agents<sup>1</sup> in an outdoor environment using relative range information obtained through Radio Frequency (RF) signal strength measurements. The agents considered have no self-localisation capabilities, but they must be localised relatively to other moving agents that can potentially have accurate absolute position information (for example GPS position). An application of this tracking and localisation task can be found in the mining industry. Mines are an extremely hazardous environment where very large machines such as mining dump trucks have to operate alongside personnel or other smaller vehicles such as light vehicles,<sup>2</sup> and where all parties also interact with each other. This interaction is sometimes the cause of accidents. Although safety standards are continually improving, unfortunately, several accidents still occur every year involving this type of environment. Sometimes these accidents result in

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<sup>1</sup>In this thesis an agent is considered to be a vehicle, for example light vehicle or truck, or personnel operating in a mine and fitted with equipment as part of a protection system.

<sup>2</sup>Light vehicles include 4WD, utility cars, etc.

fatalities or in the best case only with equipment damage. The Mine Safety and Health Administration (MSHA) record all incidents occurring in mines in the U.S.A. [58]. In 2006 there were 72 fatal accidents, with 15 accidents attributed to powered haulage. Three of these accidents resulted in fatalities caused by mining haul trucks, where for example a truck ran over a light vehicle and subsequently a person died. Certainly this is an outcome that is not desired and the mining industry strives to improve the situation through the development of technical systems that reduce the risk of these accidents occurring [76,77,79].

The research presented in this thesis is motivated by the present situation in mining operations, where too many accidents involving mining haul trucks occur due to limited driver visibility from these large, heavy and therefore dangerous machines. Suitable protection systems providing or improving situation awareness can prevent some of these accidents and thus save lives and protect equipment. This thesis researches the challenges in localisation and tracking associated with this fundamental problem and presents a RF based protection system that can offer reliable protection to personnel and light vehicles operating in close proximity to the mining haul trucks.

## 1.2 State of the art

Localisation and tracking algorithms rely on correct process and measurement models. These models describe how a certain process evolves and how measurements relate to the process under consideration. Selecting an unsuitable model can lead to a catastrophic failure of the algorithm and, depending on the application, this might also lead to serious consequences for man and machine. The major part of this thesis deals with the development and application of a suitable measurement model for the proposed RF protection system.

RF propagation models to date have been developed for different purposes. The majority of the available models were developed for communication purposes, and deal with the task of ensuring a certain level of quality for the wireless communication link. The models are designed for a specific environment [13,96] such as an outdoor urban or rural environment or an indoor office environment. Surveys and comparisons [80] of the available models show that all these models capture, to varying degrees, the complexity and accuracy of the fading effects [86,87] and the influences of the propagation mechanisms (reflection, diffraction and scattering) as they inevitably occur in the real environment. They take into account factors such as the installation location of the antennas, or the terrain profile. The Okomura et al. Model and the Hata Model are typical of outdoor propagation models, and the ray-tracing technique suitable for indoor as well as outdoor environments. It is common to divide the models into outdoor or indoor propagation models dependent on the application. An additional distinction is made between statistical and deterministic models. Statistical

models are based on extensive measurements, while deterministic models are based on the theory of electromagnetic wave propagation and often also a detailed knowledge of the environment [80].

In contrast to the number of models ensuring the quality of communication, only a small number of RF propagation models and RF sensor models have been specifically developed for the mobile robot localisation and tracking task. Having a good sensor model is a key requirement for accurate localisation. The propagation models commonly used for localisation usually do not satisfy this requirement as they were developed for communication purposes and not specifically for the localisation task. A notable exception here is the ray-tracing technique, which can provide high accuracy through the inclusion of a multitude of parameters such as properties of the environment or geometrical considerations [80], albeit at a very high computational cost. This is probably the reason why this model hasn't been employed in localisation and tracking applications.

For localisation and tracking, the most commonly used model is the free space propagation model or a modification of it, the  $n$ th power law. For this model the path loss exponent is not taken to be two, but in general  $n$ , and depends on the environment [35]. The model is simple and captures (only) the core component of the RF signal propagation. This is exactly the reason why it does not allow for accurate localisation and tracking. The Wall Attenuation Factor model (WAF) as described for the RADAR application [8] builds on the above model, with the inclusion of an additional term accounting for attenuation as it occurs from walls in an indoor environment. The breakpoint model used in [82] is another variant of the free space propagation model, where the distance domain is divided into two regions in which the free space loss is approximated with different coefficients. The SpotON system in contrast [43,44] fits deterministic quadratic functions to Received Signal Strength Indicator (RSSI) data to map distance to the signal strength readings. Among the probabilistic RF sensor models, the one presented in [42] takes into account the antenna pattern of Radio Frequency Identification (RFID) tag readers and assigns discrete probabilities of detection inside specific regions of the antenna pattern. Another probabilistic RF sensor model builds on the deterministic free space propagation model and expands it through the addition of a Gaussian random variable describing the variance of the measurements given a certain range [70]. The Binary model [6] and the Distance-bound model [38,75], which are related to each other, put constraints on the estimated range. The Binary model limits the measured range to an upper bound, whereas the Distance-bound model also provides a lower bound, effectively giving a range interval. These two models are suitable for constraint-based localisation algorithms [25]. Through the use of a signal strength map it is possible to circumvent the explicit need for a sensor model. Such maps can be augmented by a simple exponential sensor model dealing with random variations in the sensor measure-

ments as shown in [45]. Signal strength maps are one of the techniques predominantly used for indoor localisation [3, 83]. Recently Gaussian processes [16, 33, 34, 55, 73] have become popular in robotics and they also have been applied to the RF localisation task.

The models from this variety of available RF sensor models and techniques are often not suitable for localisation tasks. This may be due to different reasons such as heavy computational load inherent to the ray-tracing technique or the necessity for an a priori map of the specific operational region as is the case with the signal strength maps. This may also be simply because the models cannot provide sufficient accuracy in localisation.

Probabilistic localisation and tracking algorithms are often based on the Kalman Filter (KF) or the Extended Kalman Filter (EKF) [40, 48, 56], Particle Filters [5, 39, 74] or Histogram Filters (Occupancy Grid (OG) type filters) [21, 29, 30]. OG filters are used predominantly in the mapping area. In contrast to the KF, where the state and the observations are approximated by a (continuous) Gaussian function, the Particle Filter (PF) and the Grid-Filter approximate the distributions by a finite number of samples or grid cells. Although this discretisation is an approximation only, its power lies in the fact that it can also approximate non-Gaussian distributions. This is of importance as RF propagation, specifically the behaviour of received signal strength vs. distance, is non-Gaussian and when dealt with in a probabilistic framework leads to non-Gaussian likelihood-functions for sensor observations. For such cases appropriate tracking and localisation algorithms like PFs and Histogram Filters (HFs) are more suitable. Presently there are two dominant areas of research that are related to signal strength localisation. The first deals with sensor network localisation [61, 85, 93] where static network nodes with unknown position have to localise themselves using signal strength measurements to so called anchor nodes. These anchor nodes have absolute position information and serve as reference nodes. The other research area comprises the task of localising and tracking moving agents relative to other anchor nodes [8, 42, 43, 45, 82]. This topic is explored in this thesis. The task of multi-sensor localisation, also presented in this thesis, necessitates the consistent fusion of the sensor information from multiple homogeneous sensing sources [28].

To the authors knowledge there has been no qualitative analysis published explaining the mechanisms that prevent RF-RSSI based range estimation from achieving high accuracy localisation. In particular there has been no publication in the robotics community so far, describing why the commonly used  $n$ th power model is not suitable for accurate robot localisation and tracking, or which conditions have to be met to be able to do so. In [31] the localisation accuracy of different signal strength based localisation algorithms is compared. The authors conclude that based on their experimental comparison there seem to be fundamental limitations on the achievable accuracy, but no further explanations for their conclusion are presented.

The RF sensor model as developed in this thesis aims at providing higher accuracy for the localisation task. This leads to the situation that the developed models are often specific to particular environmental conditions, such as type of ground etc, for which they were developed. In practice the environmental conditions are not constant and therefore a variety of models has to be developed for use in various possible conditions. As the agent moves through different areas and experiences different conditions the correct model given the specific area and conditions has to be chosen and used for the localisation task. Using Bayesian Decision Theory (BDT) a mechanism to choose the correct model is developed in this thesis. BDT is commonly used in the area of pattern classification [26], where the task is to classify a pattern (signal). Applications can be found in the area of quality control [84].

### 1.3 Research hypothesis

This thesis sets out to show that the  $n$ th power model, currently predominantly used in mobile robotics as the sensor model for RF based localisation, is not suitable for high accuracy localisation, as it does not depict the real occurring signal propagation closely enough. It also presents an alternative RF sensor model and filtering approaches to achieve higher accuracy in RF based localisation applications.

### 1.4 Contributions

This thesis deals with tracking and localisation of mobile agents, such as people and light vehicles, using RF signal strength. Standard RSSI receiver readings, as obtained through the integration of the received signal over a certain period of time, are used as measurements for the localisation and tracking process. The thesis explores this topic in the context of the development of a protection system suitable for the mining industry. The requirement for such a system is that the task of localisation and tracking takes place in an outdoor environment. More specifically the thesis addresses the issues of probabilistic RF sensor modelling and suitable algorithms for the 2D localisation and tracking task.

Its main contributions are:

- A demonstration that the commonly used  $n$ th power model is not sufficient for accurate range based localisation as it does not realistically depict the actual signal propagation.
- The development of a new, probabilistic sensor model for RF signal strength based localisation. For a given signal strength measurement the model returns the likelihood to be at a particular distance. The model is multi-modal and closely reflects the real

occurring signal propagation. Furthermore, a qualitative discussion of the expected localisation accuracy with regards to the sensor model properties is provided. The sensor exhibits behaviour where the measurement variance is dependent on the magnitude of the received signal. This leads to a bias in the measured range, which in turn affects the localisation accuracy adversely.

- The development of probabilistic localisation and tracking algorithms to exploit the advantage of the newly developed sensor model for range only localisation (relative range information only). The model is multi-modal and therefore needs algorithms that can handle this characteristic of the sensor model.
- A comprehensive study to demonstrate the advantages in localisation performance of the newly developed model with respect to the widely used  $n$ th power model. The advantages and disadvantages using Bayesian filtering techniques, such as the KF, PF and OG, in conjunction with these models are also presented and the findings are underlined with simulation and experimental results. This evaluation is of interest to ensure that the chosen filtering algorithm handles the multi-modal nature of the observations correctly, thus providing an improved estimate of the location.
- Investigation into the effect of using single RF sensor and multi-sensor systems employing the model developed, and presentation of a comprehensive analysis of the expected localisation and tracking quality. Simulation and experimental results are provided to validate this contribution.
- The development of algorithms to include multiple sensor model candidates for the localisation task in a given situation. The use of BDT as a possible application for correct sensor model selection is also demonstrated.

## 1.5 Structure of the thesis

**Chapter 1** forms the introduction to this thesis. It provides the context in which this thesis is set, and presents the state of the art with regards to the topic researched. The contributions of the thesis are presented and the structure of the thesis is outlined.

**Chapter 2** expands on the context of the thesis. It introduces the problem of close proximity accidents in mining and shows reasons for these accidents. Subsequently the available protection systems are listed. The chapter finishes with the presentation of the hardware that is used in the experimental parts of the thesis.

**Chapter 3** presents the fundamental theory of RF propagation and RF modelling. The RF propagation mechanisms are presented, followed by a selection of important and

commonly used RF propagation models. The distinction between deterministic and statistical models, indoor and outdoor models is made and examples are presented. The focus in this chapter is on the models used in mobile robotics, though some models from the area of communication will also be shown. The  $n$ th power model and the two-ray model are highlighted as they are important for the later parts of the thesis.

**Chapter 4** shows RF sensor modelling and localisation & tracking using range-only RF sensors. It introduces the filtering algorithms considered, the Kalman Filter, the Particle Filter and the Histogram Filter, and presents the process models, constant velocity model and Gaussian kernel convolution, as used in the trackers. A discussion follows, as to why accurate sensor modelling is important, especially when the process model is poor, as is the case of a motion model for people.

Furthermore, this chapter shows the consequences of using the considered tracking techniques with multi-modal observations. The multi-modal observations have to be approximated so that they can be used in the filters. The ramifications of this approximation for the tracking result will be shown.

**Chapter 5** is concerned with the main contributions of the thesis: a thorough presentation of the development of a new sensor model for RF sensors is given, together with a qualitative comparison of this model to the  $n$ th power model. Important properties of the new sensor model that affect the tracking quality are also discussed.

2-dimensional range-only localisation using RF sensors is also presented in this chapter. In this context the topics of data association, sensor fusion and the effect of ranging errors are presented.

Finally, BDT for model selection presents an algorithm for the selection of the correct sensor model from multiple (situation specific) sensor models dependent on the environmental conditions. This is important as the accurate description of the sensors makes the sensor models situation dependent, and the model might need to be switched when the situation changes.

**Chapter 6** presents results obtained from simulations and from field experimentation. These results underline the theoretical considerations from the previous chapter. Results from 1-dimensional and 2-dimensional range-only tracking using the three different probabilistic filtering methods, the two motion models presented and the new sensor model in single-sensor and multi-sensor configurations are shown.

A discussion of the results is provided.

**Chapter 7** summarises the contributions of this thesis. It provides conclusions regarding the work presented and shows possibilities to extend and continue the work.