Chapter 7

Conclusions

This thesis addressed the theoretical and practical issues related to Radio Frequency (RF)-Received Signal Strength Indicator (RSSI) based range-only localisation and tracking of mobile robots or people in unstructured outdoor environments. It showed the complexity of this task and the main issues that need to be addressed to successfully achieve high-accuracy localisation. These issues can be summarised as follows:

- Accurate sensor modelling: To date, RF sensor models applied to mobile robotics applications are often very simplistic. To increase the accuracy in the localisation process, increased attention must be given to the generation of accurate sensor representations.

- Use of suitable tracking methods: Accurate probabilistic RF sensor models have been shown to be multi-modal. The employed tracking filters need to be able to adequately represent the sensor models used.

In this thesis different aspects related to the two points previously mentioned are addressed. Solutions were presented and demonstrated with simulation and experimental results.

In this chapter the contributions of this thesis are summarised and presented. Possible future extensions to the work presented in this thesis are discussed. Final concluding remarks are provided.

7.1 Summary of contributions

To date, mobile robot localisation using RF sensors has often employed simple uni-modal sensor models as the observation model. Alternative methods created signal strength maps which bound the application to the region where the map was created. The advantage of the simpler models is that they can be applied easily using probabilistic techniques as simple as the standard Kalman Filter (KF). One important problem with the *simpler* sensor models (not the mapping technique) is that they do not represent the real occurring RF signal propagation accurately.

This thesis' contributions explain why the simple models fail and show how RF localisation accuracy can be improved. Unsolved issues that need to be considered to further increase the localisation accuracy are also described.

7.1.1 Demonstration that the nth power model is not sufficient for accurate range based localisation

This thesis showed and explained why RF-RSSI range-only based mobile robot tracking and localisation algorithms relying on the nth power model cannot achieve high accuracy localisation. The fact that the signal mean is approximated only by an inverse exponentially decaying function misrepresents the real occurring signal drop. To obtain higher accuracy in the localisation process, it is necessary to ensure that the mean signal attenuation model is improved to better reflect the reality.

7.1.2 Development of an accurate Radio Frequency sensor model

Based on the conclusion that the nth power model is not sufficient for precise range-only localisation, a probabilistic sensor description based on geo-referenced measurements was developed that addressed the issue of accurately modelling signal propagation behaviour. Indeed, the resulting sensor model reflects the signal behaviour in a manner close to the real occurring signal attenuation. The accurate description of the sensors used in the tracking and localisation application is a key component of the successful algorithm.

The developed sensor model was analysed with respect to its expected performance when employed in a tracking architecture. It was shown that, like other sensor models, it exhibits a bias, leading to biased measurements.

7.1.3 Development of probabilistic tracking techniques to be used with the new sensor model

Probabilistic 2D tracking algorithms based on the KF, Particle Filter (PF) and Histogram Filter (HF) were developed and evaluated in conjunction with the new multi-modal sensor description as the observation model for these filtering techniques. The filters used in the application need to be capable of representing the state and measurement distributions correctly as they occur. Of the three filtering techniques, the KF was shown to be unsuitable for the measurement likelihood functions (and as a consequence also state distributions) occurring with RF sensors when they are described by the new sensor model. The other two techniques proved to be better suited for the application with RF sensors. Nevertheless, using multi-modal measurement functions is not straight forward in localisation and has a higher computational load. This thesis showed that the use of more accurate sensor models for RF sensors has the potential to increase the localisation accuracy when coupled with a suitable tracking algorithm.

7.1.4 Evaluation of single-sensor versus multi-sensor localisation systems for Radio Frequency-Received Signal Strength Indicator based range-only localisation

As the RF sensors only provide range information derived from RSSI measurements, more than one sensor observation from a spatially different location needs to be present to resolve the inherent absolute bearing uncertainty. As the number of sensors at spatially different locations increases, the uncertainties and ambiguities are reduced. This thesis also showed that even in the case of multiple sensors, it is not guaranteed that only one hypothesis remains. It is possible that multiple hypotheses arise, where the true location is among these hypotheses. From this, it can be concluded that it is necessary to show caution when using the Maximum Likelihood (ML) estimate as the most likely position as it sometimes may give the wrong result with multiple hypotheses. As a result, the state distribution as a whole needs to be analysed very carefully to provide a single value for the state.

7.1.5 Experiments

Simulation and experimental results were presented to underline the theoretical findings and validate the applicability of the herein developed multi-modal sensor model and the performance of the algorithms.

The use of simulations is important to highlight certain properties of the sensor models and the tracking algorithms in isolation from other effects under constant conditions.

Experiments were conducted to confirm the performance of the algorithms and the sensor models under real conditions.

7.2 Future research

The work presented in this thesis can be extended in several ways, both theoretical and practical. They are presented in the following subsections.

7.2.1 Pre-calculation of the signal mean function

The sensor model shown in this thesis was developed using geo-referenced measurement pairs to obtain the underlying distance-RSSI function, known as the signal mean function. As the measurement pairs are specific to the location they are taken from, the model obtained from these measurements is specific to the same location or a similar location.

Mobile robots often have maps of their environment available, which is especially true in indoor environments, but is also common in outdoor environments. It will be worthwhile to investigate the possibility of pre-calculating the important signal mean function based on map information available, instead of obtaining it experimentally. Obtaining the experimental data needed for the sensor model is very tedious and requires a lot of time and measurements. The pre-calculation could be eventually done using the multiple-ray model, similar to the more computationally expensive ray-tracing techniques that were presented as capable of providing an accurate representation of the signal propagation. If such a pre-calculation could be achieved a significant reduction of the effort to deploy RF-RSSI based range-only localisation would be the result.

7.2.2 Compensation mechanisms for the sensor bias

As shown in the thesis, even with a perfect sensor an observation model as given in this thesis would exhibit a bias. This in turn will lead to incorrectly estimated distances. A compensation of this bias would allow the accuracy of the estimated distances to further increase and thus increase the accuracy of the whole localisation and tracking process.

Further theoretical analysis of the mechanisms leading to the bias observed needs to be done prior to the development of such a compensation. However, the practical value of such an analysis and the successful implementation of compensation mechanisms, if possible, is not to be underestimated. Apart from the herein used RF sensor there are definitely more types of sensors that exhibit a similar behaviour (i.e. their measurements are biased) and would benefit from a compensation mechanism.

7.2.3 Sensor fusion to enhance the system capabilities

The potential to fuse the RSSI based location information with position information obtained elsewhere is apparent. Global Positioning System (GPS) position information will be possibly inaccurate when close to large structures, and more likely accurate when further away. The behaviour of the RF-RSSI based location estimates is the opposite, with better distance estimates for close ranges and worse estimates for larger ranges. A combination of these two types of sensors should be complementary and beneficial to the overall performance in the localisation and tracking process.

7.2.4 Deployment of the system in a real environment and Real-time implementation

Finally, with the target application in view, the next step would be to install a system permanently in a mining environment, develop the sensor models and evaluate their performance. Unanticipated issues related to the pursued higher accuracy localisation using RF sensor could be encountered.

The implementation of the tracking algorithms in real-time is a further point for future work. To date, the data have been processed off-line, but ultimately the final application demands real-time performance. The demands might not be too stringent, with updates of the position probably required only about every 500ms or even more, leaving a lot of time for processing. However, the way the sensor model was described in the parametric form with the large number of parameters still poses a significant computational burden. Consequently, in the context of the real-time implementation, parameter reduction may become important. This opens the question of finding a way to reduce the parameters of the Fourier approximation in order to preserve and not alter the properties of the measurement likelihood functions.

7.3 Summary

This thesis presented the issues related to improving the accuracy of RF-RSSI based range-only localisation. An improved localisation accuracy, if obtained with such low-cost sensors, is obviously attractive for commercial reasons, and may allow for the introduction of important safety systems or other applications, which so far may have been hindered by the cost of installing a system that provides the necessary accuracy.