

Utilizing RFIDs for Location Aware Computing

Benjamin Becker¹, Manuel Huber², and Gudrun Klinker²

¹ EADS InnovationWorks, Germany
Advanced Industrial Design and Visualization
81663 München

benjamin.becker@eads.net

² Technische Universität München, Germany
Institut für Informatik
Boltzmannstraße 3, 85748 Garching b. München
[\[huberma, klinker\]@in.tum.de](mailto:huberma@in.tum.de)

Abstract. This paper focuses on the possibilities of utilizing infrastructural RFIDs for location aware computing.

A key to automated computer aided work is location and situation awareness. This allows the system to operate independently from direct user input, minimizing the impact on the original process. For demonstration purposes a large area tracking system using existing RFID technology and infrastructure is developed and evaluated. As a first possible application we embed the system into an aircraft cabin.

The localization procedure is based on the coordinates of the RFID transponders detected by the RFID reader, as well as the orientation information measured by a gyroscope. Position estimation is accomplished through an iterative algorithm, optimizing the position of the antenna's readability field with respect to the currently visible tags. The average error is below half a meter.

Possible use cases range from maintenance assistance to way finding in commercial shops or underground parking lots.

1 Introduction

In order to automatically adapt to the ever-changing contexts in which a user may perform, situation and especially location awareness emerged as a key concept in ubiquitous computing. A system that is aware of the user's location is enabled to react to the current demands without explicit input and may assist in various novel means.

Unfortunately location information is not always easily accessible. Often tracking either relies on public infrastructure which may not be present everywhere, especially indoors, or on specialized infrastructure which usually has to be deployed at a high cost per area. Furthermore the installation of specialized hardware is likely to be unfeasible in certain environments because it usually is obtrusive and distracting. The consequence of these constraints is the idea to use whatever technology is present as infrastructure for position estimation.



Fig. 1. Computer Assisted Maintenance Worker

In an industrial scenario it is possible to introduce new technology in a controlled manner and thus it is more accessible in this manner as more diverse technologies are likely to be present. Especially RFID technology, which already has seen some attention in ubiquitous computing, is at the moment predominately used by supply chain management and life-cycle management applications. Therefore RFID technology is expected to become more and more ubiquitous in the near future and thus may be part of our common environments, even possibly enabling its use in domestic environments.

We focus on the industrial setup of aircraft cabin maintenance (Figure 1) where we can assume already present RFID tags distributed in the cabin for quality assurance as part of our infrastructure. We will show that using these tags it is possible to perform inside-out tracking and pose estimation.

We demonstrate this on a first prototype of an automated maintenance support system. Location awareness herein reduces the need for direct user input since the system is able to detect the current state of the worker.

Computer aided maintenance and automated worker support for maintenance tasks in general have already been studied in the past (see for example [1] or [2]) and their benefit has been established. This allows us to mainly focus on the characteristics of the tracking concept including scalability, low impact integration and precision.

2 Exposition

The following paragraphs will describe the prototype's overall hardware setup as well as the currently used position estimation algorithm. This is still a prototype and will require further adaption for integration into concrete future scenarios.

2.1 Technical Background

In contrast to existing infrastructural large-area outdoor trackers like GPS and GSM, there is a general lack of scalable and robust large-area trackers working indoors. This paper introduces the possibilities of using RFID technology for localization and tracking in large, dense indoor areas. The prototype illustrates the concept on the example of an aircraft cabin testbed, where RFID tags have been deployed independently for the setup and evaluation of various use cases.

As already stated, logistics, quality assurance and life-cycle management are major domains of RFID technology. To match these requirements, tags vary in levels of complexity from simple ID transmitters to smart cards. Passively powered tags use the energy transmitted via the RF field for the communication response whereas active tags depend on an additional power source. Currently there are two common physical communication layers [3]: near field (LF at $134.2kHz$, HF at $13.56MHz$ and $27.125MHz$) and far field (UHF at $433MHz$ or $868MHz$ (EU) and $915MHz$ (US), MW $2.45GHz$ or $5.8GHz$) which especially differ in their operating distance which ranges up to few centimeters in the first case and typically up to $6m$ in the second case. Active powered tags reach further and often implement additional features like complex encryption - but suffer from a short lifespan and additional maintenance issues due to their battery.

Summing up, active tags allow more complex applications at a higher investment per tag. Usually they are used to identify only few but special objects for a short period of time, whereas passively powered tags are often used as a long-term identification of structural parts.

For our aircraft cabin scenario we focus on passively powered tags which are being used for long-term quality assurance of structural parts. These support our assumption that RFIDs are massively distributed as part of the infrastructure. Recent use cases show the need for long range readability beyond $1m$, from which our proposed tracking method profits much more than it would from short range RFIDs, as these would severely limit the operating volume.

2.2 Related Work

Tracking methodologies are generally classified into outside-in and inside-out tracking. For outside-in tracking a global set of observers determines the positions of all participating entities, whereas in inside-out tracking each participant determines its pose independently on its own using landmarks in the environment. Similarly existing approaches for RFID based tracking can be classified into these categories. The inside-out RFID tracking uses distributed tags and a single mobile reader for the position estimation of the reader whereas outside-in uses a certain number of fixed readers to track a set of mobile transponder.

Outside-in based systems generally suffer from the need to distribute numerous readers in the tracking area, impeding the possible scalability to large areas, due to complex communication needs and high investments.

Although outside-in tracking does not match the general constraints of the aircraft use cases, it does use the same technological basis and therefore our system should be able to compete with it. Even commercial applications exist [4], using angle of arrival for the tracking of proprietary, active ultra-wide-band tags. Another system [5] demonstrates the possibility to enable tracking by distance grouping of transponders by varying the antenna's power.

Inside-out based tracking was already used to update a robot's position estimation [6] by reading tags with known location. Another promising approach [7] is introducing the *Super-Distributed RFID Tag Infrastructure*. This scenario uses a small robot vehicle equipped with a very short-range RFID reader pointing downwards. The tags are distributed on the floor using their ID to reference a specific position.

2.3 Prototype Scenario

The prototype demonstrates the possibility to achieve 6DOF localization and tracking of a mobile device in an aircraft cabin using a long-range reader and a cloud of distributed passive tags, taking a gyroscope's current orientation estimate into account. The goal of this application is to allow automated maintenance support based on location awareness. Maintenance of air crafts is time critical as every minute on ground means lost revenue to the airline.

Clearly, the more promising approach for our case is an inside-out based tracking system, having no or little impact on the environment by bundling the required hard- and software on a single mobile device. The system's design for a single reader and inexpensive passive RFID tags allows us to cover a large area with little investment. Besides, often the required infrastructure is already present from other RFID applications as listed in the prior paragraph. Also a mobile computing device can be easily extended with additional sensors like a gyroscope or WLAN tracking, increasing range, robustness and precision of the localization algorithm.

Hardware Setup. Since RFIDs are only just being introduced in the aircraft production and maintenance process the tags in the prototype's cabin mock-up were added supplementarily. This paragraph describes how the tracking system was embedded into the aircraft cabin and gives additional detail about the hardware in use.

It is useful to have a large and reliable reading range to increase robustness as well as the position estimation quality. The RFID tags which had already been deployed in the aircraft cabin testbed are passive ultra-high-frequency transponders, which match these requirements (Figure 2, *Rafsec G2 ShortDipole* at *868Mhz*). The reader used was a *Feig LRU2000 UHF Long Range Reader*. Since neither this nor any other investigated reader made any tag quality metrics (such as received signal strength indicators) available, each scan only resulted in

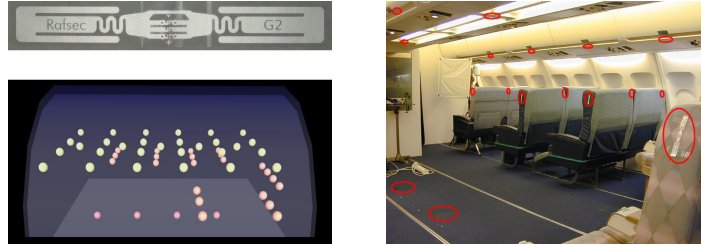


Fig. 2. RFID Tags Distributed in Aircraft Cabin

binary “detected” or “not-detected” information per tag. The miniature long-range reading device (Figure 3) is equipped with a directional antenna. The antenna’s gain increases the reading range along a single axis, allowing this system to detect tags up to a distance of *6.0 meters*. As illustrated in Figure 2 (right and lower left), the transponders in this scenario are distributed within the aircraft’s cabin, especially attached to the hatrack, the seating and the floor panels. In the final scenario in a real aircraft cabin usually every major structural part has its own identification tag, giving a far denser distribution. For measuring the current orientation, a gyroscope is directly connected to the antenna (Figure 4) with a precalibrated offset transformation.

Basic Localization Concept. The localization procedure is based on two sensors: the RFID reader and the gyroscope. The reader’s output is a list of tags read by the antenna within the last *200 milliseconds*. Note that these measurements only constitute the existence of the relevant tags in the reading range of the antenna and do not contain further distance information. The developed RFID tracking system has three basic characteristics:

- A large number of RFID tags are attached to structural parts of the cabin. For each of them the exact location and ID are known and available to the system as part of the Digital MockUp (DMU) data.



Fig. 3. RFID Reader



Fig. 4. Xsens Gyroscope

- A gyroscope measures the current orientation. This is used internally to increase the accuracy of the position estimate and returned as part of the pose estimation.
- The reading range of the RFID antenna is taken into consideration. It has to be determined beforehand.

The localization is based on the coordinates of the currently detected transponders, which can be derived from the database. The antenna is estimated to be at a position from where it is able to read all currently detected tags best. This is accomplished through an iterative process which imposes requirements on how the detection range is modeled, as seen in the following section.

In our case the position of each RFID tag and the corresponding ID was measured in a preprocessing step. Hopefully this can be automated in a future scenario by having predefined IDs and positions of tags on certain constructions or building parts. This assumption is realistic, since RFID technology is in the process of being integrated into the aircraft manufacturing process.

The setup of the following algorithm is intended to strongly reduce computational cost of the pose estimation. This is required since mobile devices often lack computational power in favor for mobility and uptime.

Antenna Readability Model. Before actually using the system, the detection range of the RFID reader’s antenna has to be determined. Due to missing details on the assembly of the antenna this has to be empirically estimated through experiments.

To distinguish the readability field some tests were run. Since the system uses a directional antenna with a rotationally symmetric RF field, the dimension of the testbed was reduced to a 2D plane through the central axis of the antenna. Numerous tags were attached to polystyrene cubes and placed on a grid to evaluate the reading range and probability, resulting in a discrete readability field.

For each point \mathbf{p} relative to the antenna the position estimation algorithm requires a scaled displacement vector from the antenna model. This vector $v(\mathbf{p})$ indicates in which direction the antenna needs to be moved to increase the chance of detecting a transponder at location \mathbf{p} . A scalar $d(\mathbf{p})$, defining the intensity of the displacement vector of a tag at this position is used to increase the influence of a wrongly positioned tag on the pose estimation.

Both will be derived from the probability of a tag being read. Since real-time computation of the readability for all tags is computationally expensive, a gradient field was derived by interpolation (Figure 5) which serves as a lookup table. The resulting gradient field is used to scale the displacement, which is shown in Figure 6. Both fields use coordinates in the antenna’s reference frame. The antenna is placed at $\mathbf{p} = (0, 0)$ and the point with the maximum reading possibility is located at $\mathbf{p}_{max} = (0, 0.85m)$.

Optimization of the Position Estimate. The reader scans the antenna field for visible tags during $100ms$ slices. Initially the position estimation assumes

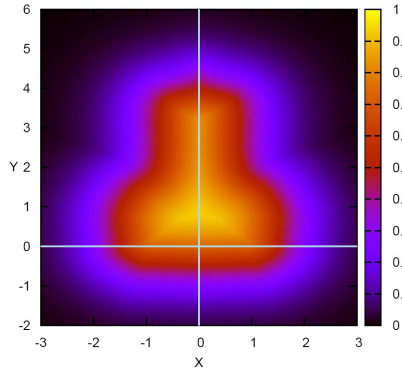


Fig. 5. Antenna Readability

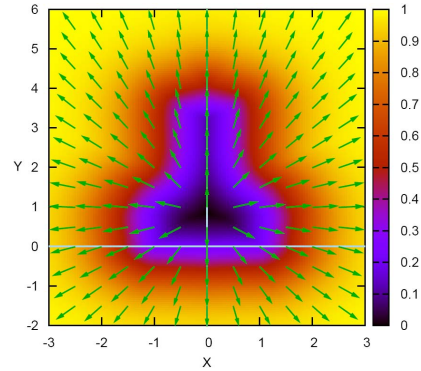


Fig. 6. Displacement

that the antenna is in the centroid of the visible tag positions. At each step a simple optimization procedure is performed.

First of all the visible tags are rotated into the reference frame of the antenna by applying the inverse of the orientation measured by the gyroscope. This relative position is projected onto the 2D plane and used to access the readability as well as the displacement field. In the next step the median over all displacement vectors is computed and added to the current position resulting in a new position estimate. The estimated quality of this position is calculated as the sum over the readability of all detected tags, taken from the readability field. Iteratively this procedure optimizes the position estimate until a lower border has been reached.

When finished the position as well as the likeliness with the highest quality rating is returned. In case no tags have been detected, the current position is kept untouched.

2.4 Prototype Analysis

This section focuses on the evaluation of the technical properties of the prototype and compares it with other existing setups.

Error Analysis. The setup for the test is shown in Figure 7. For the estimation of the ground truth position an optical infrared tracker is used, allowing the reflective marker on the antenna to be localized within millimeter precision. Also the offset between the infrared reflection marker and antenna was calibrated beforehand. This assures that the entire tracking system used for validation and testing introduces a negligible error compared to the expected precision of the RFID tracking.

We present here only a one minute excerpt from our test runs, which exemplifies the typical performance of the system. The mobile device was moved in the cabin with varying orientations. The currently visible tags and the resulting position estimation of the RFID tracker as well as the ground truth position



Fig. 7. Antenna with IR-Marker and *A.R.T.* Tracking System

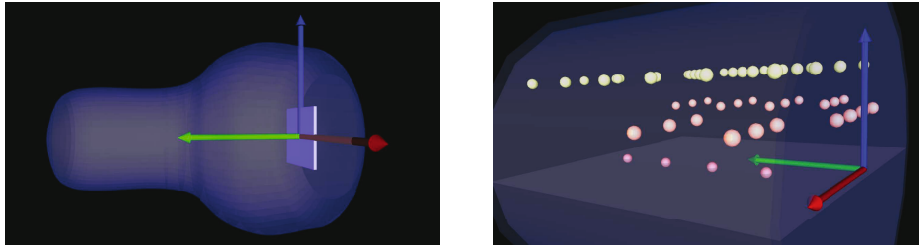


Fig. 8. Antenna Field (Median Readability) and Cabin Coordinates

were timestamped and logged. In a post-processing step the recorded data was examined to determine the precision and to analyze the current setup.

To differentiate the error induced by the distribution of the tags and the antenna model, the coordinate system's axes are distinguished with a trailing 'a' for antenna or 'c' for cabin. In Figure 8, the cabin has the x_c axis (red) pointing to the side, the y_c axis (green) to the front and the z_c axis (blue) to the ceiling. The antenna's coordinate system has the x_a axis pointing to the side, the y_a along the antenna's normal and the upward axis z_a .

The overall performance of our approach can be extracted from Figure 9. It shows the error distributed along all three axes of the cabin as well as the average error across the entire testing time. The output is the raw data taken from the position estimator without any filtering or continuous position estimation for jitter reduction. The Euclidean distance between the RFID tracker's estimate and the ground truth ranges up to *1.5 meters* with an average of *0.48 meters*.

In the beginning of the test run, the antenna was moved while pointed towards the front of the cabin. This results in a small y_c axis error since a more homogeneous distribution of the RFID tags (Figure 8, right) allows the antenna model to fit perfectly with its long reading range along its y_a axis. Therefore the effect is homogeneous in both reference systems.

In the time range between *10* and *40 seconds* the antenna was additionally pointed upwards and downwards while still moving through the cabin, increasing the error along the z_c axis. The uncertainty along the other two axes as well as

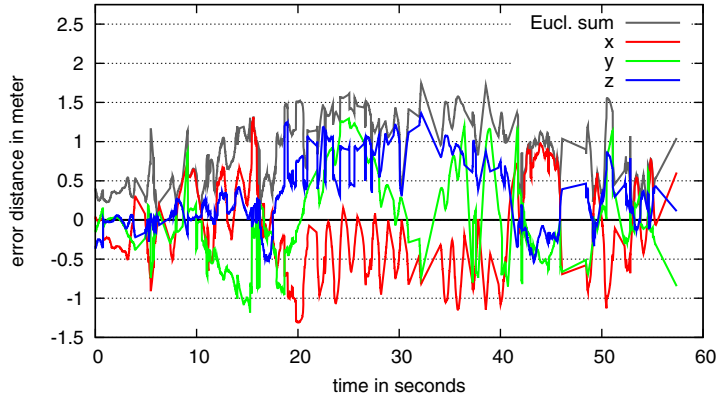


Fig. 9. Error in the Test Run in the Cabin’s Coordinate System

the overall error are also increased, since the antenna’s reading field is mainly outside of the cabin’s volume where no tags were placed.

Within the final time interval beginning at *40 seconds*, the antenna’s position was kept still but was rotated mainly around its z_a axis and therefore often pointing along the side of the cabin (x_c axis). This shifts the error between the y_c and the x_c axis. The distribution density of the tags towards the side of the cabin is also inappropriate.

Not only the distribution and the homogeneity of the tags are important for a proper function of the algorithm, also the number of tags used for the position estimation is of interest. Looking at Figure 10, it is evident that the simple approach to use the centroid of the tag cloud is inferior to the optimization based on the antenna model. The overall median error is reduced from *0.71* to *0.48 meters*. It is evident that the possible uncertainty introduced by the antenna’s long reading range in direction of the y_a axis could be compensated

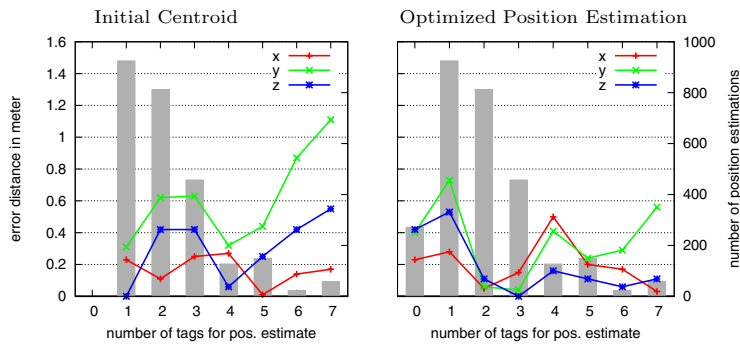


Fig. 10. Error in the Antenna’s Reference Frame (x, y, z) and Histogram (gray bars) with Respect to the Number of Detected Tags

with the orientation based method. The errors on the x_a and z_a axis could be improved only slightly.

For the case of zero detected tags the error is high because without measurement information supplied no further estimation can be performed. In the case of a single tag the algorithm's estimate induces an even larger error. This indicates that a tracking using a motion model, based on preceding estimates, could achieve an increased performance since a good initial estimate seems superior to the estimation based on a single tag. Single tag discoveries often occur when the reader is pointing directly into an obstacle, reducing the range of the RF field.

Although the error should be indirectly proportional to the number of tags this can not be derived from our current test results. As the histogram in Figure 10 illustrates, only about 3% of the frames have more than 4 tags detected. Nevertheless it seems obvious that the error increases in a high detection case. A possible reason for this can be traced back to the reader buffering recently read tags when a quick rotation is performed, resulting in more detected tags but partially from an outdated orientation.

Although neither the algorithm nor the implementation can be expected to be optimal, the results clarify four main error sources in the system setup:

- inhomogeneous distribution of tags cause the position algorithm to fail
- low density of RFID tags yield an inferior pose estimation
- obstacles changing the antenna's reading probability field increases the error
- accumulation of visible tags over a certain period of time introduces an error when quick rotations are performed

These characteristics need to be considered in future optimizations of the system.

Error Evaluation and Comparison. Considering the simple algorithm and optimization model used, the achieved quality is encouraging. As the results clarify, the antenna model and the position estimation algorithm are not optimal. Nevertheless it is obvious that an algorithm using a representation of the antenna model in combination with the orientation information of a gyroscope can significantly increase the quality of an RFID tracker.

For a comparison with existing RFID based tracking systems, the outside-in based approaches are analyzed first. Although they have a totally different target application and differ largely from our setup it is important to see what results are possible when using RFID technology at ideal conditions. Disregarding the already mentioned disadvantages, the results are only of slightly better quality regarding precision of the position estimate. The tracker *Ubisense* reaches only slightly better results with 95% of the measurements having an error below 30cm [4]. The passive outside-in system *landmarc* ([5]) achieves an median error value of about one meter. Both systems highly depend on the number of readers used in the tracking area.

Inside-out based approaches, as used in the fields of robotics, can benefit from the advantages of continuous tracking with control inputs from the robot's steering sensors. Besides this, the localization is reduced to a 2D position estimation.

The system presented in *Super-Distributed RFID Tag Infrastructure* [7] allows a high quality position estimation. When a tag is detected, the short reading range of the antenna provides a high accuracy localization, giving the robot the chance to correct its internal estimate. This still suffers from a major drawback: When carried by a worker and therefore without control input, continuous tracking fails since the short reading range implicates very seldom tag discoveries.

2.5 Application and Further Use Cases

For our maintenance application the tracking is precise enough to embed a location aware assistance software. It is possible to guide the worker to the correct frame of the aircraft and to prioritize the tasks according to his current position, so that maintenance tasks in the current working area are favored and thus minimizes time spent between tasks. Also it is possible to reduce user input which would occupy the worker.

The use of a tracking system allows extending the existing workflow of a mechanic. Nowadays it is common to have a digital task list on a mobile device to verify that all important maintenance tasks have been performed correctly. With the additional location sensitivity it is possible to guide the worker towards the next task and automatically give additional information regarding the current step.

For further scenarios, it will be interesting to see if RFID technology is feasible for standalone tracking, as supporting tracker for initialization of a more precise but local tracking method (e.g. optical model-based tracking)[8] and for large-area tracking. Also it is promising to evaluate RFID technology as an additional source of information for ubiquitous computing or Augmented Reality applications regarding location awareness and object identification. Furthermore RFID based infrastructure can serve as an additional tracking modality in ubiquitous tracking setups[9], extending it to otherwise inaccessible environments.

As stated before RFID technology is expected to become more common and enter areas of our daily life. As a consequence this also can be seen as a low cost tracking infrastructure becoming ubiquitously available which can lead to numerous applications.

One such envisioned possibility is assisted wayfinding and navigation in supermarkets. This scenario further is supported by the fact that today many consumer products already start to be tagged by RFIDs, as some preliminary field studies show. Another similar scenario could be the installation of tags in underground parking lots to facilitate customer routing and orientation between parking decks and cars.

3 Conclusion and Outlook

Our system extends the existing approaches to a complete 6DOF tracker by combining the 3DOF orientation of the device with the 3DOF position optimized considering the antenna's alignment.

The precision of the position estimate is of similar quality as the existing commercial outside-in tracking systems. Contrary to those approaches, the tracking system presented here allows simple and cost effective scaling for tracking within large areas. A major difference to the existing inside-out tracking systems is that it does not require the control input of a robot to function, allowing it to be applied for tracking mobile devices.

This prototype confirms the idea of using RFID technology as a basis for location aware computing. The precision is acceptable for location based applications but leaves room for improvement. Our work shows that there is a high potential in using RFID technology for tracking purposes.

For different scenarios it might not be feasible to spend additional money on a gyroscope to reduce the error but use a less directional antenna taking the centroid of the detected tags as pose estimation.

Further Improvements. One possible way to improve the application is to examine the readability of tags in detail. Not only the antenna's characteristic defines the probability of a tag to be detected, but also the orientation of the tag's dipole in the RF field. This leads to the idea not only to store the position of the distributed RFID tags in a database but extend it to a 6DOF pose. Also different reader hardware setups will be investigated. Other readers allow dynamic reconfiguration of the radio parameters and also do not exhibit the buffering problem observed above. Different antennas with more pronounced directional radiation patterns may also influence the performance of the system.

Another influence on the readability is the close environment of the tag, the material it is attached to as well as any material preventing it from being read by the reader, in case it is placed in the objects inside. This should also be taken into account when trying to estimate the reader's position.

Currently also ignored, yet of major importance to the position estimation, is the impact of undetected tags on the position estimate. An estimate not only becomes more likely if the detected tags are mapped perfectly to the antenna model but also must decline if many tags within the readability field are invisible.

Our next extension will be a *Kalman Filter* based model that takes a tag list as measurement input and compares this to the readability derived from the antenna model. This allows the algorithm to also exploit undetected tags and to reach an even better estimate. Additionally the *Kalman Filter* will use an internal motion model for continuous tracking.

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