Improving FMCW-based Object Tracking Using Phased Array Antennas Combined With Sigma-Point Kalman Filters

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Abstract—Frequency modulated continuous wave (FMCW) radar techniques are methods of choice when it comes to localization-based applications in harsh (e.g., dusty, smoky) environments. In this paper, we propose a significant improvement to the current industry standard by replacing hardware and software components with advanced counterparts.

I. INTRODUCTION

An industry standard high-precision localization system is given by local positioning radar (LPR) [7]. This is the baseline setup we use for comparing purposes in this paper. LPR is designed to work based on a 5.8 GHz FMCW-radar in environments for which the following problems apply:

- combined outdoor/indoor tracking (e.g., fork lifters), so often no GPS signal available
- uncomfortable environment, especially dusty, dirty or foggy which makes usage of optical systems like lasers impossible
- high precision demands which can not be fulfilled by civil GPS receivers

Like GPS, it uses the exactly known information about the position of its beacons (transponders) to generate the position estimation. An object under observation is equipped with a “base station”, in fact an entire embedded system containing an antenna, an FMCW signal generator module and a signal processing hardware/software system. The base station broadcasts an FMCW signal and all available transponders respond to this signal via an own transmit channel to allow distinct identification of the transponder ID.

An omni-directional antenna, mounted onto the tracked object, emits upsweep and downsweep microwave chirps. The echoes of all contributing transponders are processed within the frequency domain (FFT) and the radar Doppler equations,

\[
\Delta f_{\text{up}} = \frac{8Bd}{cT} - f_0 \cdot \frac{v}{c}
\]
\[
\Delta f_{\text{down}} = \frac{8Bd}{cT} + f_0 \cdot \frac{v}{c}
\]

where \( B \) = denotes the bandwidth, \( T \) = sample period, \( d \) = object to transponder distance, \( v \) = object to transponder speed and \( c \) = speed of light. A special derivative of a sequential extended Kalman filter (EKF) in round-robin scheduling calculates an estimation of the object’s location. This setup uses kinematic and observation models within the EKF algorithm which combines observations (measurements) with prior state estimations to aim towards best-guess overall system state estimation. The initial position setup is obtained by multilateration numerics. In a perfect environment with no reflections and distortions, LPR’s resolution is within ten centimeter range.

This paper will give a detailed theoretical explanation why this setup is not sufficiently suitable to fulfill high-accuracy requirements and present an approach to overcome some of the limitations. This is done by applying two changes to the system. We will use a custom-design antenna array to reduce common multi-path errors which leads to a more stable signal availability. Furthermore, we will demonstrate situations of significant improvement of system state estimation by replacing the original sequential EKF algorithm by a generic sigma-point Kalman-filter SPKF engine. This paper focuses on a two-dimensional coordinate plane, however there is no doubt that these improvements would be found in a three-dimensional test setup as well.

II. IMPROVING THE ANTENNA

For localization based on the outlined concept it is essential that the antenna is able to receive the transponder signal from any direction. If its characteristics violently prefers a certain direction, chances are high that position calculation accuracy degrades because many measurements from a certain direction can not be incorporated into the filter algorithm, thus reducing the absolute number of usable samples per cycle. Because of this, usually omni-directional antennas are used which aim towards minimization of direction preference. These antennas are common industry standard and well-understood developments. But in fact the transponder echo concept raises another problem when it comes to localization, especially in indoor setups. It is necessary to have a direct line-of-sight configuration for as many transponders as possible in order to get an accurate position estimation.
Fig. 1. Typical indoor scenario for localization. The base station can not distinguish between a multi-path signal’s pathways.

In figure 1 this situation is illustrated. In case the walls don’t absorb too much of the signal power, it’s practically impossible to tell the difference between the line-of-sight signal and its reflected twins. As the result, reflected signals might erroneously be taken for the direct line-of-sight signal which would lead to a wrong position estimation.

To solve this dilemma, we present in [1] a solution based on an array of 16 patch antennas in a cylindrical topology (figure 2). Suitable control mechanisms allow to form 16 beams of which each one covers about 22.5 degrees in the \((x, y)\)-plane and can uniquely be enabled or disabled. This antenna has proven to perform significantly better in experimental one-dimensional multi-path scenarios and is therefore our method of choice for the achieved improvement to FMCW-based two-dimensional tracking. Please refer to [1] for details about the antenna design.

![Array of 16 uni-directional antennas, mounted on a cylindrical surface](image)

III. REPLACING THE EKF BY SPKF

The EKF is an extension to the Kalman filter which uses Taylor approximation to overcome the classic limitation of acting as optimum minimum mean square error estimator (MMSEE) in the unlikely case that the entire state-space is purely linear. It uses exactly the same numerical framework as the Kalman filter, however for the calculation of the state covariance matrix, precision is mangled by first order linearisation.

Especially the state covariance estimation is known to degrade because of linearisation especially in highly non-linear processes. To improve tracking filter accuracy with non-linear state transfer functions \( f() \) and observation propagation functions \( h() \), a new approach of MMSEE has been under academic research for some time. This improvement, the class of sigma-point Kalman filters (SPKF) represents today’s cutting edge MMSEE. The most significant difference is that it does no longer perform updates to the state covariance matrix based on a Taylor approximated state model, instad it applies a non-linear state transfer function to all distribution density-representative sigma-points and samples the state covariance from scratch. This scheme is known to model most processes perfectly to second order, for a pure spatial Gauss-Markov-process even to third order. The theoretical explanation is given in [3]. The sigma-point Kalman filter has already proven to perform more accurate than the industry’s standard EKF in several research projects, for example in [4] and [5]. For the tracking filter toolkit \( libf \), which is in active development right now, a numerically efficient SPKF implementation, the square root unscented Kalman filter (SR-UKF) has been chosen. Probably the most interesting property of this filter is that it comes with no extra computational costs compared to the EKF. Usually we can expect a slightly larger memory footprint in real-world applications but today’s computers shouldn’t have a problem with that. However, still the industry is hesitating in replacing their EKF implementations by UKF derivatives, for the main reason that the actual implementation of an efficient SR-UKF is very complex if it needs to be done from scratch. With \( libf \), we will provide a toolkit which allows rapid deployment of native C/C++-applications, thus enabling relatively easy replacement of existing EKF algorithms by the superior SR-UKF. This is exactly what we have done for this experimental setup.

IV. EXPERIMENTAL SETUP AND MODELING

To verify the theoretical approach that the phased array antenna combined with the SPKF outperforms the standard omni-dimensional antenna, a difficult physical setup has been chosen. This tracking method has specific problems with metallic surfaces as they practically replicate identical “virtual” transponders. This introduces a significant difficulty to extract all necessary information from the spectrum to evaluate
the Doppler equations (1). The LPR system relies on an edge detection algorithm to browse the spectrum for valid transponders. The more multi-path artifacts are present, the lower the likelihood to locate the correct edges will be. The phased array antenna can efficiently eliminate nearly everything which is outside a beam’s 22.5 degree lobe. Especially for object tracking close to corners this is a tremendous advantage.

Our setup consists of six transponders, two pairs of three in an almost equally spaced orientation. Within the covered area between these beacons, the object under observation with its base station is located and meant to describe an almost rectangular movement with one intermediate when switching from x-only-movement to y-only-movement and back. The room itself is highly contaminated with metallic objects such as columns, doors and partially the ground itself. For reliable results we slightly modified the origin LPR measurement principle. The base station with the antenna probe is moved to the next location manually and precisely before taking a measurement snapshot. Because of this, tracking is based on transponder-distance estimation entirely. The main reason for this is that LPR is already a mature and tightly integrated embedded system and applying all necessary changes to make it take control of the phased array antenna independently would have been far over the top for a proof-of-concept survey. Instead just the experiment is performed and the data processing can be done offline.

The experiment is illustrated in figure 4. The transponder setup is shown as well as the reference track and the major obstacles. In the gray marked sector B we can expect multi-path distortion caused by the metal doors whereas in the gray range A the dominant error source is most likely the two large metal columns. In the green highlighted area a relatively clean signal from at least five transponders can be expected. The two filters are set up as follows:

- The genuine sequential LPR EKF which is stable, mature and has constantly been improved over the last years with all its additional features is used. It is a highly specialized derivative of standard EKF methods to address this specific application. It iterates over all non-gated transponders sequentially for the entire algorithm. The observation noise covariance $R$ in only a 2-by-2 matrix containing the variances for a transponder’s distance and velocity measurements. This means it does not compute a minimum mean square error estimation among all available transponders, instead a least square solution to the error of a single transponder’s distance/velocity observation vector is calculated. This may result in a better overall estimation if a small number of transponders is available after gating but can also decrease accuracy if many transponders contribute. We will recognize both effects later. It also includes a particularly smart observation distance pre-gating algorithm which calculates an “ellipse of trust” for any subsequent transponder measurement and omits distance estimations which reside outside this ellipse. A post-gating algorithm which ensures that the velocity resides in a reasonable range is applied as well. This gating scheme is also an adaptive algorithm which performs surprisingly well for most situations. Significant parts of this filter have been developed in [2].

- The SR-UKF is used “as is” with a very simple observation gating which simply drops a transponder distance value if its deviation from the observation estimation exceeds a certain threshold. This algorithm is not adaptive. Post-gating is not performed.

The gating criteria are necessary because signal multi-path is not a noise component. It is an annoying, destructive measurement influence which is more or less deterministic if it is possible to identify its sources. Unfortunately LPR is not able to do that and their peaks are far beyond measurement error modeling. Consequently, because MMSE methods do not exclude parts of the observation vector completely because of an unexpected variance level, instead they will render the estimation useless if not gated, for both the EKF and the SPKF observation gating is a must.

The process model is quite simple and not bound to specific properties of this particular setup to maintain the same “general” setup as the commercial LPR version. For presented 2D-tracking based on a position/velocity vector, we use for the state transfer function $f(\cdot)$,

$$
\begin{align*}
x'_{k} &= x'_{k-1} + \Delta t \cdot \dot{x}_{k-1} \\
y'_{k} &= y'_{k-1} + \Delta t \cdot \dot{y}_{k-1} \\
\dot{x}_{k} &= \dot{x}_{k-1} \\
\dot{y}_{k} &= \dot{y}_{k-1}
\end{align*}
$$

where $\Delta t$ is the cycle time to the next measurement, and the observation transfer function $h(\cdot)$,

$$
d'_{k,i} = \sqrt{(x'_{k} - t_{x,i})^2 + (y'_{k} - t_{y,i})^2 + (\Delta z)^2} \forall i \quad (2)
$$

where $i$ denotes the set of transponders, $d$ the measured distance, $t$ the transponder’s position with respect to the reference coordinate plane and $\Delta z$ the height difference between the antenna and the transponder. The process noise is modeled as a standard piecewise white constant acceleration model. For
one coordinate, e.g. $x$ this means,

$$Q_x = \begin{bmatrix} \frac{\Delta t^2}{2} & \Delta t \\ \frac{\Delta t^2}{2} & \Delta t \end{bmatrix} \cdot \begin{bmatrix} \frac{\Delta t^2}{2} & \Delta t \\ \frac{\Delta t^2}{2} & \Delta t \end{bmatrix} \cdot \sigma_{x,x}^2$$

where $\sigma_{x,x}$ reflects the acceleration-caused uncertainty of the velocity information, thus the entire process noise matrix defaults to:

$$Q = \begin{pmatrix} \Delta t^4 & 0 & \Delta t^3 & 0 \\ \Delta t^3 & 0 & \Delta t^2 & 0 \\ 0 & \Delta t^3 & 0 & \Delta t^2 \\ 0 & \Delta t^2 & 0 & \Delta t^2 \end{pmatrix}$$

(4)

This matrix is fed directly into the EKF initialization cycle whereas the UKF is initialized with the upper triangular Cholesky-factorization $S_Q$ such that $Q = S_Q^T \cdot S_Q$.

The observation noise model for the SR-UKF is even more simple. Because in a real-world scenario it is usually not feasible to rely on coupled variances among different transponders, whereas for example in this particular experiment one might assume a strong relation between transponder number four and five, all transponders are assumed to have the same variance and no covariance to the others, hence the observation noise root is assumed to,

$$S_R = I \cdot \sigma_o$$

(5)

where $I$ is the unit matrix and $\sigma_o$ the absolute base station to transponder distance estimation uncertainty. Because transponder velocity measurements are not used in this experiment, they are not processed by the $h()$ function thus not included in the $S_R$ matrix.

V. ANALYSIS AND RESULTS

After obtaining all raw data measurements, it is interesting to benchmark the tracking filters with the omni-directional antenna because it can be expected that the SPKF shines with worse measurements. Figure 5 shows one loop of the experimental track filtered by the LPR EKF.

![Fig. 5. The loop with the default LPR EKF](image)

As expected, the sections A and B which are gray marked in figure 4 are critical to LPR’s desired accuracy of 10cm to 20cm. Multi-path effects cause that many of these position estimations are based on only three to four transponders, and very likely some of these measurements are not the direct line-of-sight signals. The entire region A ($y = 10.80 m, x = 16m \ldots 29m$) is over-dominated by the gating algorithm rather than the tracking filter. The UKF results (Figure 6) aren’t any better; because of the simpler gating method partially even worse. The generic UKF’s standard deviation is indeed 5cm higher than the LPR EKF’s.

![Fig. 6. The loop with the SR-UKF](image)

Section B suffers from similar problems, but differently signed. The EKF is obviously much more susceptible to the metal doors. The reason for this effect is the aforementioned sequential method. The multi-path signals lie within the gating ellipse, so the distance values aren’t dropped but they are actually no line-of-sight signals. Because the UKF calculates an error-minimal solution to the transponder distances among each other whereas the LPR EKF does not, instead it only relies on a transponder-to-next-transponder uncertainty, the generic UKF is far less sensitive to this problem. As a result, its estimated position curve matches the real position tighter, yielding a 4cm better standard deviation in this critical section.

In fact, the only part where we can truly compare the tracking filters is the green section of figure 4 because the gating allows virtually all transponder signals to pass through. So the UKF always gets a complete observation vector and the LPR EKF does not need to prematurely exit its iteration over all transponders. The result can be anticipated by visually comparing the lower left quadrant of the figures 5 and 6. There are only two situations in which the EKF is slightly more accurate; in the beginning of the green section ($x = 14.46m, y = 6.72m \ldots 5.52m$) and one single sample at ($x = 20.96m, y = 2.43m$). The debug log file indicates that in all these cases no more than four transponder signal made it through gating. Consequently, UKF results are more accurate in this part of the track (table 1).

The single bad sample at ($x = 20.96m, y = 2.43m$) is exceptionally worth mentioning. This is the only sample based on less than five transponders in the entire range ($y = 2.43m, x = 15.56m \ldots 25.76m$), the only sample worse than EKF’s estimation in this range and this $x$-position is exactly between the $x$-coordinates of the metal columns near the upper part of the track. At the very same $x$-position in section A the LPR EKF also yields its worst position estimation of the entire track. This is a very good example to demonstrate how
sensitive to multi-path effects the LPR system really is. As the result of the filter benchmarking using the omni-directional antenna it can be said that the overall performance of both filters covering the entire test track is nearly identical as the standard deviation difference is only 6mm as given in table I. However an important result is that as soon as the signal reception is good enough to process at least five of the six transponders, the generic SR-UKF is constantly superior to the genuine LPR EKF.

In the last setup the omni-directional antenna has been replaced by the custom phased array antenna which is described in detail in [1], combining both new developments.

Fig. 7. The loop with the phased array, filtered by SR-UKF

The result is displayed in figure 7. It is clearly obvious that the phased array is significantly less susceptible to most multi-path effects. Although the log file shows that gating is still necessary for many samples, the antenna’s narrow lobes ensure that the direct line-of-sight signals are recognized more often in the spectrum processing instead of multi-path signals which are only slightly off, so the absolute number of correct line-of-sight signals for Kalman-Filter processing is higher compared to the omni-directional antenna. The numeric result is revealed in table I. Especially in the strongly contaminated sections A and B the improvement is beyond bliss; the standard deviation is almost as good as the omni antenna’s in the green section, even better than the genuine EKF’s performance with the omni antenna in the green section; the overall position estimation is twice as accurate. The only significant multi-path sensitivity can be observed in close proximity to the metal doors \((x = 29.38 \text{m}, y = 4.10 \text{m} \ldots 7.30 \text{m})\) and even in this zone within section A the average deviation is almost 20cm better than with the omni-directional antenna. The visual also looks cleaner; it is less scattered and no spontaneous leaps are visible.

<table>
<thead>
<tr>
<th></th>
<th>LPR EKF</th>
<th>Generic UKF</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Omni</td>
<td>Omni</td>
</tr>
<tr>
<td>Section A</td>
<td>0.283</td>
<td>0.337</td>
</tr>
<tr>
<td>Section B</td>
<td>0.390</td>
<td>0.349</td>
</tr>
<tr>
<td>Green section</td>
<td>0.142</td>
<td>0.127</td>
</tr>
<tr>
<td>Overall</td>
<td>0.237</td>
<td>0.243</td>
</tr>
</tbody>
</table>

TABLE I
OMNI-DIRECTIONAL VS. PHASED ARRAY ANTENNA: POSITION ESTIMATION STANDARD DEVIATION, IN METERS

However multi-path effects are in fact still persistent and might influence the position estimation if they reside within the 22.5 degrees every patch antenna covers. So for example the aforementioned bad sample at \((x = 20.96 \text{m}, y = 2.43 \text{m})\) between the \(x\)-coordinates of the metal columns is still an issue. At this very position, again, two transponder signals are dropped by the gating because they are way off; obviously those two signals enclose a dominant multi-path signal within the 22.5 degrees lobe.

VI. CONCLUSIONS

The main error source for the FMCW-tracking system LPR is signal multi-path distortion, not a noisy signal which is the primary target for the class of MMSEE algorithms. As a result, even a less difficult but typical real-world LPR scenario involves situations in which the errors are close to deterministic but can not properly modeled and are beyond measurement variance; Because of this, there are situations like section A and B with the omni-directional antenna, in which additional helper algorithms like gating dominate the overall filter behavior so that in one situation the genuine LPR EKF performs better, in a different situation the generic UKF.

In this paper we have shown that, whenever a direct line-of-sight is given for all transponders, the generic UKF outperforms this highly specialized sequential EKF derivative developed for LPR because of its better mathematical accuracy and numerical covariance estimation. This is reflected by the constantly better filtering results in the green section. Furthermore, replacing the generic omni-directional antenna by the custom phased array antenna establishes a tremendous performance boost to the overall position estimation. In many cases, multi-path distortions are mitigated significantly in a way that in the end more direct line-of-sight signals are available for the actual position estimation. As the result, the proposed combination of the sigma-point Kalman filter with the phased array antenna outperforms the old configuration in every tested scenario.

REFERENCES

[5] Rudolph van der Merwe, Eric Wan: Sigma-Point Kalman Filters for integrated navigation, OGI School of Science & Engineering, Oregon Health & Science University, 2004