

MCMC PARTICLE FILTER WITH OVERRELAXATED SLICE SAMPLING FOR ACCURATE RAIL INSPECTION

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Abstract: This paper introduces a rail inspection system which detects rail flaws using computer vision algorithms. Unlike other methods designed for the same purpose, we propose a method that automatically fits a 3D rail model to the observations during regular services and normal traffic conditions. The proposed strategy is based on a novel application of the slice sampling technique with overrelaxation in the framework of MCMC (Markov Chain Monte Carlo) particle filters. This combination allows us to efficiently exploit the temporal coherence of observations and to obtain more accurate estimates than with other techniques such as importance sampling or Metropolis-Hastings. The results show that the system is able to efficiently and robustly obtain measurements of the wear of the rails, while we show as well that it is possible to introduce the slice sampling technique into MCMC particle filters.

1 INTRODUCTION

Defect detection systems for rail infrastructure are utterly needed to reduce train accident and associated costs while increase transport safety. The early detection of wear and deformation of tracks optimises maintenance scheduling and reduces costs of periodic human inspections. For that purpose it is required the introduction of new technological developments that make these systems more efficient, easier to install and cheaper for rail operators. Specifically, some magnitudes are of vital importance, such as the wear of the rails, and the widening of the track, which may cause catastrophic derailment of vehicles (Canon et al., 2003).

Traditionally, this problem has been faced using human inspection, or tactile mechanical devices which analyse the profile of the tracks while installed in dedicated rail vehicles running at low speed. Current technological trends try to avoid using contact-based devices to avoid their practical problems. Some works are based on the use of ultrasonic guided waves (di Scalea et al., 2005), which allow the detection of surface-breaking cracks and sizing of transverse; and vision-based systems, that determine the presence and magnitude of visible flaws (Alippi et al., 2000). Due to the rail geometry, lasers are typically used to project a line on the rail to ease the detection of its

profile.

Regarding vision systems applied in this field, massive amounts of data are typically acquired and stored for a supervised posterior analysis stage to actually identify and locate defects. A major lack in this type of applications is the automatic fit of the model of the rail to the detections so that the potential wear of the rail could be automatically analyzed to see if it falls within the tolerances. The challenge of a vision-system in this field is to fit a planar 3D model of a rail to a set of 2D observations of laser projections in the absence of reliable visual features that generate metric patterns (a pair of points with known distance, or a known angle between imaged lines). Some authors (Alippi et al., 2000) (Alippi et al., 2002) have omitted this problem and work at image level, which includes the inherent projective distortion into their measurements. Popular computer vision tools fail in this task, such as POSIT (DeMenthon and Davis, 1995) since it does not work for planar structures, or optimisation methods, such as gradient-descent of Levenberg-Marquardt algorithm (Nocedal and Wright, 2006), which are extremely sensitive to local minima.

In this paper we propose an automatic method for rail auscultation using a vision-based system that fits a 3D model of the rail to the observations using a MCMC (Markov Chain Monte Carlo) particle filter. The method performs estimates of the proba-

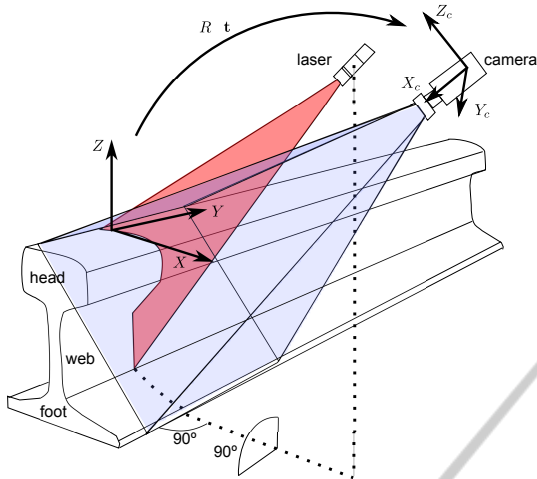


Figure 1: Set-up of the elements of the system. The laser is installed orthogonal to the rail, while the camera shows some rotation and translation $\{R, \mathbf{t}\}$.

bility density function of the model through time by applying the overrelaxation slice sampling technique, which provides accurate and robust fits while reducing the number of required evaluations of the posterior function compared to other schemes such as importance sampling or Metropolis-Hastings.

This paper is organized as follows: section 2 illustrates the architecture of the method; in section 3 the image processing techniques used for laser detection are explained; section 4 shows in detail the proposed particle filter strategy to fit the 3D model to the observations and section 5 depicts the procedure to project the 2D image elements into 3D to retrieve the actual metric error measurements. Tests and discussion are presented in section 6.

2 SYSTEM DESCRIPTION

The system has been devised to measure two important magnitudes: the wear of the rails, and the widening of the track. For that purpose, one camera and a laser are installed for each rail, which are set-up as depicted in figure 1. As shown, the only requirement is that the laser line is orthogonally projected to the rail, i.e. the laser plane coincides with $Y = 0$. The camera monitors the projected line with a certain angle to acquire images as those shown in figure 2. This angle can be any that guarantees that the laser line is observed in its projection on both the head and web of the rail.

It is noteworthy that the system does not require an exact positioning or symmetry of the cameras with respect to the rails, since the vision-based algorithm

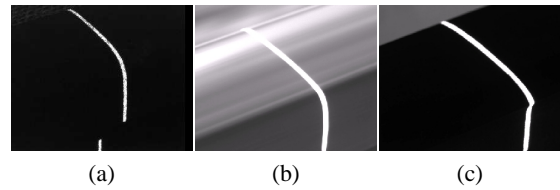


Figure 2: Examples of images captured by the acquisition system: (a) typical static image; (b) image captured during regular service, with sun reflections; and (c) severe rail head wear.

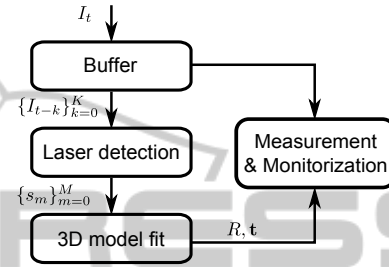


Figure 3: Block diagram of the proposed method.

automatically determines the relative position and rotation $\{R, \mathbf{t}\}$ of the cameras with respect to their corresponding rail.

Figure 3 shows a block diagram of the system. The first stage comprises the proposed method for laser line detection, which feeds the 3D modeling stage that projects a specific rail model (for instance we use the UIC-54 flat-bottom rail model) and finds the best translation and rotation parameters that makes the model fit to the observations. The last step is the reprojection of the detected points given the estimate of the model parameters to quantitatively determine the wear of the rail and the existing widening.

3 LASER DETECTION

This section describes the proposed procedure to extract the information relative to the rail profile from the images acquired by the system. In this harsh scenario two main problems arise. On the one hand, achieving a good isolation between the projection of the laser line and other illuminated elements (e.g. background elements reflecting the direct sun radiation). On the other hand, obtaining time coherent information despite the relative movement that the rails will show during regular services. The movement is caused by vibrations, curvature (the width of the track changes accordingly to the curve radius), or the relative position of the cameras with respect to the wheels (the more distance to the wheel, the more movement of the rail with respect to the bogie).

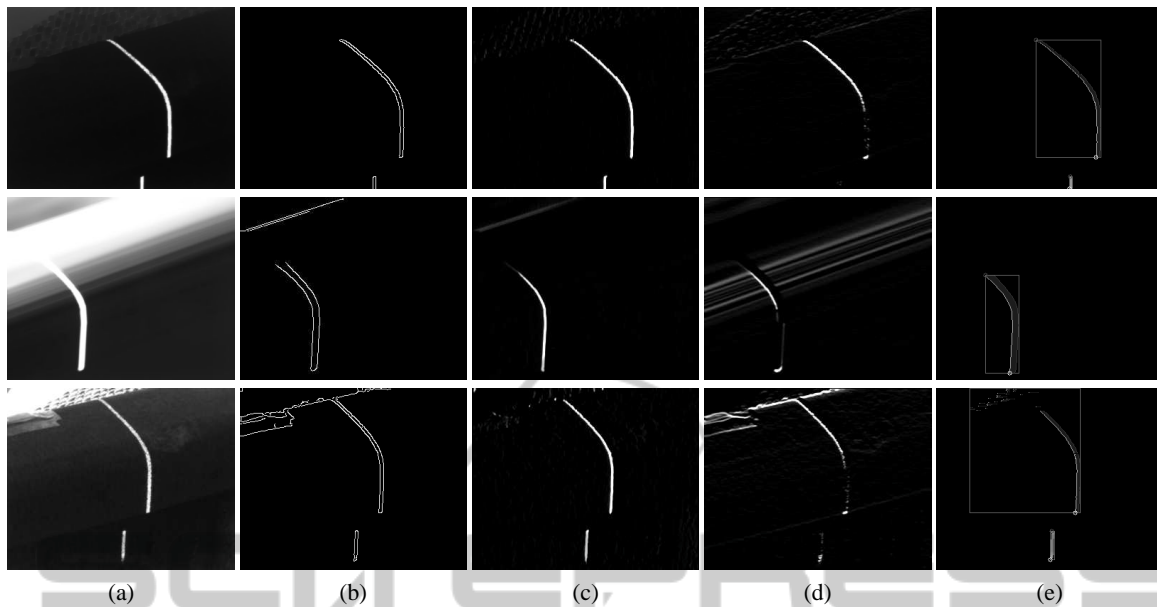


Figure 4: Examples of the proposed laser detection methodology for different cases (shown in rows): (a) original image; (b) Canny edges; (c) G_x , magnitude of gradient x -component; (d) G_y , magnitude of gradient y -component; and (e) connected component analysis.

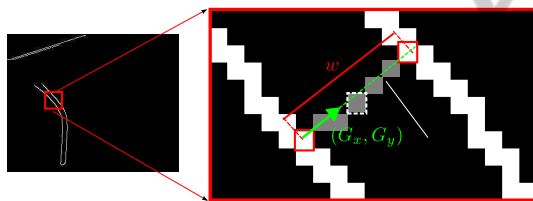


Figure 5: Estimation of the width of the laser beam. The middle point between the start and end points is used to compute the mean intensity level of the laser line.

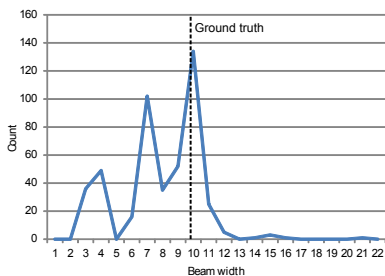


Figure 6: Histogram of width values for the example images of figure 4 middle row.

The laser line can be described by its visual characterizes. First, since we do use an infrared filter, the laser line is imaged as a bright stripe compared to the rest of the image, which remains dark (save for the reflective surfaces). Second, the laser line width can be considered fixed independently of the position in the image, since the relative distance between the

different points in the rail is too low and causes no significant perspective effect.

According to these two considerations, the proposed method carries out the following actions (which are depicted with images in figure 4). First, we apply the Canny edge detector, which identifies the edges of the image, and we keep the gradient values (G_x, G_y) it internally computes using the Sobel operator (Gonzalez and Woods, 2002). From each identified edge pixel, we search in the gradient direction the closest edge pixel and store the obtained distance as a measure of the width of the stripe (see figure 5). Since we do have edges that do not belong to the laser stripe, a histogram analysis is carried out to select the most repeated distance value w_t . An example histogram is shown in figure 6, where the ground truth value is shown with a dashed line. As shown, the detected maximum of the histogram is very close to the ground truth. This value is averaged in time to adapt the system measurements to the observations, so that we obtain $\hat{w}_{t,K} = \frac{1}{K} \sum_{k=1}^K \hat{w}_{t-k}$.

Since we do have an instantaneous estimate of $\hat{w}_{t,K}$ at each time instant (except for the very first frame), we can as well characterise the intensity level of the laser line by analyzing the intensity level of the middle pixels between pairs of edge points whose distance is close to $\hat{w}_{t,K}$. With this analysis we obtain the mean μ_I and standard deviation σ_I of the intensity values $I(x,y)$ of the pixels likely belonging to the laser stripe.

From the information extracted at pixel-level, it is possible to search for the laser stripes at a higher level. The search is carried out locating pairs of edge points that likely belong to the laser. A pair p_i is defined as a couple of points which define the left and right limit of the projected laser line and whose distance is close to $\hat{w}_{t,K}$. To reduce the algorithm complexity, we define pairs at row level, i.e.

$$p_i = \{(x_l, x_r, y) \mid |x_r - x_l - \hat{w}_{t-K}| < \varepsilon\} \quad (1)$$

where x_l and x_r are the x -coordinates of the points of the pair, y is their common vertical coordinate; and ε is an error limit that can be safely set as a percentage of the width value, e.g. $\varepsilon = 0.05\hat{w}_{t-K}$.

The intensity level information is used to classify pairs in connected groups so that the different parts of the laser projection (the corresponding to the head and the web of the rail) can be identified. This classification will allow having a better model fit. For that purpose a thresholded image is created from I using as threshold $\mu_{t,K} - 2\sigma_{t,K}$. For each pair we can define a label that identifies the connected component it belongs to, $c_i = m$.

Finally we obtain stripes as sets of pairs which belong to the same connected component of the intensity binarized image: $s_m = \{p_i \mid c_i = m\}$. From here on we will denote a pair p_i as $p_{m,i}$ where m identifies the cluster or stripe s_m it belongs to.

To reduce the impact of outliers those sets of pairs whose cardinality is lower than 3 are removed, i.e. there must be at least 3 connected pairs to define a stripe. Two main stripes are finally identified amongst the stripes. As shown in figure 4 (e) the lower vertical stripe corresponds to the rail web, and the largest one defines the head of the rail. The lower point of the head stripe will be denoted as anchor point, and used as a reference point to fit the 3D model.

4 3D MODEL FIT

To actually be capable of determining the existing wear of the rail, it is necessary to fit the rail model to the observations extracted from the images. The observation of image I_t is defined as $\mathbf{z}_t = \{s_m\}_{m=1}^M$, i.e. a set of M stripes.

The model fit must be such that describes the relative movement between the rail and the camera, so that we obtain a common coordinate system for the model and the observation and measure the potential defects.

From the projective geometry point of view, there is an unsolved ambiguity in the projection of a 3D planar model to a 2D observation with unknown scale:

a single 2D observation can be the projection of the model at different positions and distances.

Therefore, the problem consists on finding the relative translation and rotation between each camera with its corresponding rail. This way, for each camera we can define the state vector to be estimated at each time instant t as $\mathbf{x}_t = (x, y, z, \theta, \dot{x}, \dot{y}, \dot{z}, \dot{\theta})^\top$, where (x, y, z) are the translation components of each coordinate axis and θ is the rotation in the y -axis (the rotation of the other angles can be considered negligible). The last four elements correspond to the first derivative of each of the four former parameters. We will assume that the intrinsic parameters of the camera are computed at the set-up and installation stage so that the projection matrix is already computed and available.

In this work we propose to apply Bayesian inference concepts that allow us to propagate the probability density function of the state vector conditioned to the knowledge of all observations up to time t , $p(\mathbf{x}_t | \mathbf{z}_{1:t})$. Within this framework we will be able to overcome the mentioned ambiguity and achieve accurate estimates of the target coordinate systems so that the rail defects can be measured.

4.1 MCMC Particle Filter

MCMC methods have been successfully applied to different nature tracking problems (Khan et al., 2005; Barder and Chateau, 2008). They can be used as a tool to obtain maximum a posteriori (MAP) estimates provided likelihood and prior models. Basically, MCMC methods define a Markov chain, $\{\mathbf{x}_t^{(s)}\}_{s=1}^{N_s}$, over the space of states, \mathbf{x} , such that the stationary distribution of the chain is equal to the target posterior distribution $p(\mathbf{x}_t | \mathbf{z}_{1:t})$. A MAP, or point-estimate, of the posterior distribution can be then selected as any statistic of the sample set (e.g. sample mean or robust mean), or as the sample, $\mathbf{x}_t^{(s)}$, with highest $p(\mathbf{x}_t^{(s)} | \mathbf{z}_{1:t})$, which will provide the MAP solution to the estimation problem. Compared to other typical sampling strategies, like sequential-sampling particle filters (Arulampalam et al., 2002), MCMC directly sample from the posterior distribution instead of the prior density, which might be not a good approximation to the optimal importance density, and thus avoid convergence problems.

If we hypothesize that the posterior can be expressed as a set of samples

$$p(\mathbf{x}_{t-1} | Z^{t-1}) \approx \frac{1}{N_s} \sum_{s=1}^{N_s} \delta(\mathbf{x}_{t-1} - \mathbf{x}_{t-1}^{(s)}) \quad (2)$$

then

$$p(\mathbf{x}_t | Z^t) \approx \frac{1}{N_s} \sum_{s=1}^{N_s} p(\mathbf{x}_t | \mathbf{x}_{t-1}^{(s)}) \quad (3)$$

We can directly sample from the posterior distribution since we have its approximate analytic expression (Khan et al., 2005):

$$p(\mathbf{x}_t | Z^t) \propto p(\mathbf{z}_t | \mathbf{x}_t) \prod_{s=1}^{N_s} p(\mathbf{x}_t | \mathbf{x}_{t-1}^{(s)}) \quad (4)$$

For this purpose we need a sampling strategy, such as the Metropolis-Hastings (MH) algorithm, which dramatically improves the performance of traditional particle filters based on importance sampling.

Nevertheless, there are other sampling strategies that can be applied in this context and that improve the performance of MH, reduce the dependency on parameters and increase the accuracy of the estimation using the same number of evaluations of the target posterior. Next subsection introduces the slice sampling algorithm, that was designed to remove the problem of random walk detected in MH (Neal, 1998; Neal, 2003).

4.2 Markov Chain Generation

Particle filters infer a point-estimate as an statistic (typically, the mean) of a set of samples. Consequently, the posterior distribution has to be evaluated at least once per sample. For high-dimensional problems as ours, MCMC-based methods typically require the use of thousands of samples to reach a stationary distribution. This drawback is compounded for importance sampling methods, since the number of required samples increases exponentially with the problem dimension.

In this work we propose to use the overrelaxed slice sampling strategy (Neal, 1998), which avoids random walks in the generation of the Markov Chains and thus allows obtaining better descriptions of the posterior distribution.

4.2.1 Slice Sampling

This technique generates a chain of samples, $\{\mathbf{x}_k\}_{k=1}^N$ from a arbitrary target pdf, $p(\mathbf{z})$ (Neal, 2003). The only requirement to apply this algorithm is that the value $p(\mathbf{x})$ can be evaluated for any given value of \mathbf{x} . As described by (Bishop, 2006), the slice sampling improves the results, in terms of efficiency, of typical sampling approaches based on the Metropolis-Hastings (MH) algorithm (Gilks et al., 1996). MH has an important drawback that makes it inefficient for the proposed application as it is sensible to the step size, given by the proposal distribution. If it is chosen too small, the process behave as a random walk, which makes the algorithm converge very slowly and, on the contrary, if it is too large, the rejection rate may be

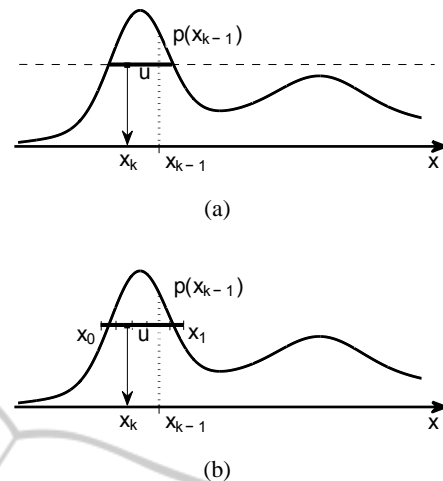


Figure 7: Univariate slice sampling: (a) the uniform u value determines the slice through $p(x)$; and (b) the practical implementation uses fixed length steps to determine the range in which x is uniformly sampled.

very high, hence not achieving accurate results. The advantage of the slice sampler is due to its ability to automatically adapt its step size according to the characteristics of the probability density function.

For a better understanding of the slice sampler, let us consider first the univariate case. Slice sampling works by augmenting x with an auxiliary random variable u and then sample from the joint (x, u) space. Given the previous sample x_{k-1} , u is uniformly drawn in the range $[0, p(x_{k-1})]$. Fixed u , the sample x_{k-1} is obtained from the “slice” through the distribution defined by $\{x : p(x) > u\}$. This criterion is illustrated in figure 7 (a). Nevertheless, it is difficult to find the limits of the slice and thus to draw a sample from it. For that reason an approximation is done by means of creating a quantized local slice, delimited by x_0 and x_1 as shown in figure 7 (b). To obtain these limits, the value $p(x)$ is evaluated at left and right of x_{k-1} using fixed length steps (the quantification step) until $p(x) < u$. The next sample, x_k , is obtained by uniformly sampling on this range (iteratively until $p(x_k) > u$).

For multidimensional problems, the one-dimensional strategy can be applied repeatedly on every single dimension to obtain the samples.

4.2.2 Overrelaxed Slice Sampling

The overrelaxation method consists on the automatic generation of a new sample given the defined slice without the need of using a uniform random sample between the slice limits. When the slice is defined, the next sample value x_{t-1} is defined as the symmetric point between the middle of the slice limits and the

start point x_{k-1} .

This simple step reduces the rejection rate of samples in many situations, since the probability of the symmetric point x_{t-1} to have a function value lower than u is very reduced (it only will occur if the previous point was actually in the limit of the slice).

4.3 Likelihood Function

The likelihood function determines the evaluation of each sample of the chain $\mathbf{x}_t^{(s)}$ with respect to the observation at each time instant. Formally, this function determines the probability of observing \mathbf{z}_t given a certain state vector hypothesis $\mathbf{x}_t^{(s)}$.

In our case, the observations correspond to the detected laser stripes, while each sample $\mathbf{x}_t^{(s)}$ determines a hypothesized position and rotation of the 3D model. With the camera calibration information we can project this model to the image and define a cost function that determines how good the projected models fit to the detected stripes.

The model can be defined as a set of coplanar control points $\{c_i = (X_i, 0, Z_i)\}_{i=1}^N$ in $Y = 0$. Written in homogeneous coordinates we have $\{\mathbf{X}_i = (X_i, 0, Z_i, 1)^\top\}_{i=1}^N$. For each sample proposed by the particle filter, we do have a translation and rotation of the model which is applied to each control point:

$$\mathbf{X}_i^{(s)} = R^{(s)}\mathbf{X}_i + \mathbf{C}^{(s)} \quad (5)$$

The result is projected into the image plane using the camera projection matrix: $\mathbf{x}_i^{(s)} = P\mathbf{X}_i^{(s)}$.

The likelihood function can be defined as the weighted sum of two functions. One of them related to the distance between the anchor point of the projected model and the observed strokes, $p(\mathbf{z}_t, \mathbf{x}_{t,a}^{(s)})$. The anchor point is the point that separates the head and the web of the rail. The second term is related to the goodness of fit of the rest of the model, $p(\mathbf{z}_t, \mathbf{x}_{t,b}^{(s)})$:

$$p(\mathbf{z}_t | \mathbf{x}_t^{(s)}) = \alpha p(\mathbf{z}_t, \mathbf{x}_{t,a}^{(s)}) + (1 - \alpha) p(\mathbf{z}_t | \mathbf{x}_{t,b}^{(s)}) \quad (6)$$

The first term, related to the anchor point is defined as a normal distribution on the distance between the observed and reference point:

$$p(\mathbf{z}_t | \mathbf{x}_{t,a}^{(s)}) = \frac{1}{\sqrt{2\pi}\sigma_a} \exp\left(-\frac{1}{2} \frac{d^2(\mathbf{x}_{t,a}^{(s)}, \mathbf{z}_{t,a})}{\sigma_a^2}\right) \quad (7)$$

where $\mathbf{z}_{t,a}$ is the 2D position of the anchor point and σ_a is the standard deviation that characterizes the expected observation noise of the anchor point.

For the second term we first loop over the projected model points and search for the closest left and right points of a pair p_i . In case there is no pair closer

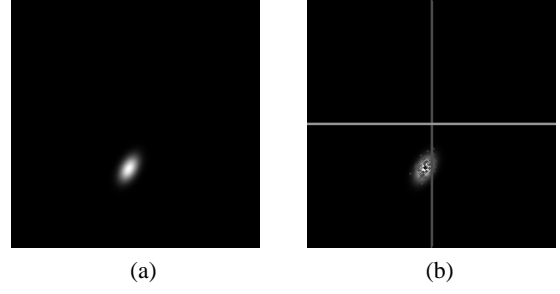


Figure 8: Visualization of the likelihood map of the (x,y) dimension: (a) likelihood map; (b) likelihood map and the set of samples obtained with the slice sampling strategy.

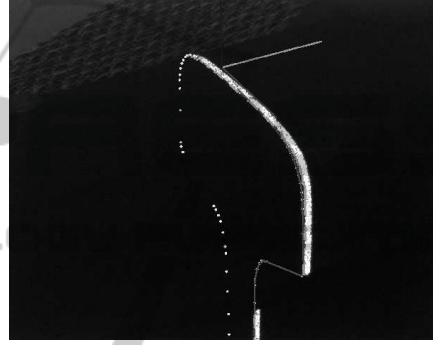


Figure 9: An example hypothesis drawn by the sampler.

than a defined threshold, no points are associated with that model point. When the points are found, the counters N_l and N_r are increased, and the distance between the model point and the left and right points are accumulated as d_l and d_r .

The second term can be then described as:

$$p(\mathbf{z}_t | \mathbf{x}_{t,b}^{(s)}) = \frac{1}{\sqrt{2\pi}\sigma} \sum_{i=\{l,r\}} \frac{N_i}{2N_{model}} \exp\left(-\frac{d_i^2}{\sigma^2}\right) \quad (8)$$

where N_{model} is the number of model points. Since this function uses both left and right fitting, it gives high likelihood values for models that project between the left and right edges of the laser beam, which enhances the accuracy of the fit compared to using only one of the edges.

For a better visualization, we have computed the likelihood value of all the possible values of the model state vector spanning its x and y -coordinates for an example image. The result can be seen in figure 8 where the likelihood map is depicted as an intensity image, where the brighter pixels correspond to (x,y) positions with higher likelihood value, and darker ones with lower value. As shown, the likelihood function is a peaked and descending function that can be easily sampled with the proposed slice sampling procedure. In figure 8 (b) we can see as well the obtained samples, which actually fall in the regions of the space

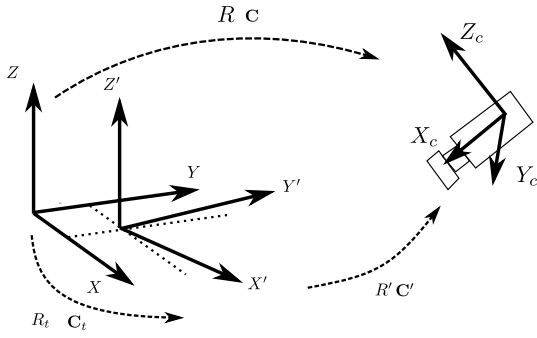


Figure 10: Relationship between the initial coordinate system $\{X, Y, Z\}$, the camera coordinate system, $\{X_c, Y_c, Z_c\}$ and the coordinate system defined after the application of the correction provided by the particle filter $\{X', Y', Z'\}$.

with higher likelihood values. In figure 9 an example model fit is depicted. The color code of the axes of the coordinate frame helps to understand the likelihood map of figure 8.

5 RAIL WEAR AND WIDENING

When the model fit has been obtained, we know the new coordinate system $\{X', Y', Z'\}$ that best fit to the observations, and that can be different from the initial coordinate system $\{X, Y, Z\}$ according to the potential relative movements of the rail with respect to the camera (typically when the train is in a curve). Figure 10 illustrates the different coordinate systems involved.

To analyze the observed profile and compare it with the reference profile it is necessary to transform back the observations from the 3D plane defined by $Y' = 0$. We can do that by obtaining the new extrinsic parameters of the camera coordinate system, $\{R', C'\}$, recompute the projection matrix P' that links 3D points in $\{X', Y', Z'\}$ to points in the image and reduce it to a 3×3 homography that defines the correspondence between points in the image plane and points in the $Y' = 0$.

The new extrinsic parameters can be computed using the initial extrinsic parameters and the values given by the filter as $C' = R_t^{-1}(C - C_t)$ and $R' = RR_t$.

The corrected projection matrix is defined as a 3×4 matrix $P' = K[R' | -R'C']$ that links 3D points in homogeneous coordinates into image points as $\mathbf{x} = P'\mathbf{X}'$. Given that the laser is projected onto plane $Y' = 0$, we can reduce P' to a 3×3 homography H' as:

$$\mathbf{x} = P' \begin{pmatrix} X \\ 0 \\ Z \\ 1 \end{pmatrix} = H' \begin{pmatrix} X \\ Z \\ 1 \end{pmatrix} \quad (9)$$

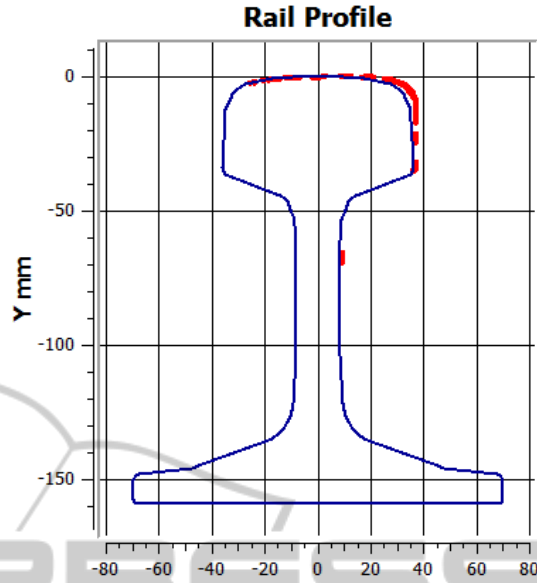


Figure 11: Comparison of the reference UIC-54 model and the backprojected laser points.

where $H' = (\mathbf{p}_1, \mathbf{p}_3, \mathbf{p}_4)$ and \mathbf{p}_i is the i -th column of P' .

The homography can be used to backproject the laser points detected in the image into a rectified view of plane $Y' = 0$ where metric measurements of the rail wear can be generated as shown in figure 11.

Finally, the widening of the track can be as well computed as the X component of the relative translation between the coordinate system $\{X', Y', Z'\}$ of the left camera and the right camera.

6 TESTS AND DISCUSSION

We have evaluated the performance of the proposed strategy applying different sampling methods but using for them all the proposed likelihood function: sequential importance resampling (SIR) (Arulampalam et al., 2002), Metropolis-Hastings (MH) (Bishop, 2006), Slice Sampling (Neal, 2003) and Overrelaxed Slice Sampling (OSS) (Neal, 1998).

Due to the dimensionality of the problem (6 DoF), the SIR particle filter requires too many samples to keep a low error fit. It has been shown that the number of samples SIR requires to that end grows exponentially with the dimensionality of the problem. In our case we have observed that SIR does not provide stable results using the proposed likelihood function for a reasonable number of particles (up to 10^4).

We have implemented three MCMC sampling methods that create Markov Chain, which are known to be the solution to the dimensionality problem of

Table 1: Efficiency comparison between slice sampling (SS) and overrelaxed slice-sampling (OSS).

Step = 1 (mm)	SS		OSS			
Num. Samp.	Num. Evals.	Error(mm)	Num. Evals.	Error(mm)	$\Delta Evals(\%)$	$\Delta Error(\%)$
10	287	3.364	266	3.213	7.32	4.49
15	430	2.732	419	2.572	2.56	5.86
25	695	1.198	650	1.363	6.47	-13.77
50	1345	1.345	1221	1.635	9.22	-21.56
100	2977	1.057	2869	1.101	3.63	4.16
Step = 2 (mm)	SS		OSS			
Num. Samp.	Num. Evals.	Error(mm)	Num. Evals.	Error(mm)	$\Delta Evals(\%)$	$\Delta Error(\%)$
10	249	3.454	283	3.553	-13.65	-2.87
15	354	2.235	313	2.322	11.58	-3.89
25	632	1.332	561	1.554	11.23	-16.67
50	1229	1.112	1095	1.223	10.90	-9.98
100	2477	0.988	2171	1.212	12.35	-22.67
Step = 4 (mm)	SS		OSS			
Num. Samp.	Num. Evals.	Error(mm)	Num. Evals.	Error(mm)	$\Delta Evals(\%)$	$\Delta Error(\%)$
10	195	5.391	166	5.489	14.87	-1.82
15	395	3.325	312	2.665	21.01	19.85
25	602	2.156	481	1.559	20.10	27.69
50	1124	1.285	901	1.082	19.84	15.80
100	2229	0.998	1844	1.001	17.27	-0.30

SIR: MH, SS and OSS. The MH, as explained in (Bishop, 2006)(Neal, 2003), suffers from the problem of the selection of the proposal function. If a gaussian function is used, the problem is to find the adequate standard deviation for that proposal. We have observed that we have a trade-off problem: on the one hand we need small deviations (less than 0.5 mm) to appropriately model the posterior function, while MH requires high values to move quickly in the state space and avoid the random-walk problem. This trade-off is not solved satisfactorily by the MH for the proposed problem.

On the contrary, slice sampling is capable of finding this trade-off, since its sampling methodology relies on finding slices which guarantees a good adaptation to the posterior function shape. This capability allows obtaining very accurate results, specially when using small values for the steps that defines the slice. The only problem of using small steps is that the definition of the slice requires often a significant number of evaluations of the posterior, which in turn reduces the performance of the system. This drawback can be partially solved using the overrelaxed slice sampling, which reduces the number of evaluations to be carried out.

We have carried out a test to compare the performance of the system using the SS and the OSS methods. The test is run to fit the UIC-54 model on a sequence with movement, to evaluate how good the sampling alternatives fit when the posterior function

is changing from one frame to the next one. The comparison is based on the computation of the fit error. The results are shown in table 1. As can be observed, we have run the tests for different step values (1, 2 and 4 mm), and for different number of effective samples to be drawn by the sampling methods. The tables shows the number of evaluations required by the methods to obtain such number of effective samples, and the fit error, which is computed as the average distance of the detected laser points reprojected into plane $Y' = 0$. The last two columns show the relative difference between these parameters for the SS and the OSS.

As we can see, for small steps both methods perform similarly, requiring the OSS between 2 and 9% less evaluations. Nevertheless, for larger steps, such as for 2 mm and specially for 4 mm, the OSS shows its best performance. With step equal to 4 mm, and 100 samples, OSS evaluates the posterior 1844 times, while SS needs 2229, both of them obtaining almost the same error fit. These results show that the OSS is capable of more efficiently representing a probability density function using the slice method, which allows faster computation without sacrificing accuracy, which remains close to 1 mm average fit error.

6.1 Future Work

This paper summarizes the achievements reached during the development of a system for the automatic in-

spection of rail wear and widening. At the time of submitting this paper the project is in a development stage, so that the results have been obtained with a preliminary prototype system. In the further stages of the project, several improvements are planned and a more detailed evaluation analysis which will integrate localisation data to the detection of rail defects.

7 CONCLUSIONS

In this paper we have introduced a new methodology for the early detection of rail wear and track widening based on projective geometry concepts and a probabilistic inference framework. Our approach presents a scenario where its usage in regular services is possible, with low cost acquisition and processing equipment, which is a competitive advantage over other manual or contact methodologies. For that purpose, we propose the use of powerful probabilistic inference tools that allow us to obtain 3D information of the magnitudes to be measured from uncomplete and ambiguous information. In this proposal we use the overrelaxed slice sampling technique, which implies a step forward in MCMC methods due to its reliability, versatility and greater computational efficiency compared to other methods of the literature that build Markov Chains.

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