Abstract—In this paper, rail track irregularity detection system based on computer vision and SVD analysis is proposed and located in the train's operator cabin near the front. Images are captured by FLEA3 camera of PointGrey, and vibration signals are collected by sensor device MPU6050 integrating 3-axis accelerometer and 3-axis gyroscope. Root mean square of gray-scale threshold Pulse Coupled Neural Network (RMS-PCNN) is used for segmentation of the rail track's image in a single loop, and the improved coupled map lattice(CML) is used for filtering the image and signifying the rail track. After perspective, the track radius can be fetched by analysis of regression. Vibration signal filtered by SVD-unscented Kalman filter(UKF) can reflect the wagon movements. In unscented Kalman filter, Cholesky is replaced by SDV in UT(unscented transform), which can solve negative definite matrix caused by covariance matrix on account of calculation error and round-off error. Also numerical stability is improved under the guarantee of filtering accuracy and the same complexity level of algorithm based on SVD-UKF. Looking up the radius record table, the corresponding threshold in gyroscope signal can be selected, and Compared to the super elevation, the invisible irregularity defects of rail bed will be found out.

Index Terms—computer vision, rail track irregularity, RMS-PCNN, SVD-UKF, gyroscope signal, super elevation.

I. INTRODUCTION

With the spread of high-speed trains and the increasing costs of road transport, railway research for technical improvements and cost reduction has increased notably during the last decade. One of the main focuses has been on the rail track irregularities. Rail track irregularities have a large effect on different aspects of railway operation, mainly system safety, train speed optimization, movement behavior and passenger comfort especially focusing on non-loaded and loaded track. To ensure a good maintenance of the rails, measurements are needed frequently, which are costly and require specific tools for different aspects of the rails geometry, and many methods are proposed.

Consequently, railway infrastructure companies invest large amounts of money in rail track maintenance yearly. A key point in this activity is regular inspection of the rail status which can avoid performance problems or unsafe situations. The critical factors of this inspection are speed and accuracy of the rails geometry measurement system. Actual developments in rail track inspection methods have been reviewed. These methods are divided into contact and non-contact measurements. The major problems with contact techniques are that they produce rail wear and due to speed requirements, and they limit the operability of the train corridor. On the other hand, the non-contact methods include accelerometer and gyroscope devices which are affected by the train vibrations and cannot assess the wear of the rail surface. Therefore optical methods seem to have advantages and have been used for accurate measurements of the rails profile. Of course the importance of acquiring accurate geometry of the rails is not only limited to railway inspection, but also involves providing information for further research on deterioration modeling.

In order to obtain this data, railway companies often use manual inventories, hand devices or the aforementioned contact tools. The manual techniques are dependent of the operator criteria and experiences, and the required long interruptions of the track operation results in costly. Whereas for the contact tools, it requires different and specific machines for every parameter to be measured, increasing the maintenance costs. In contrast, mobile laser scanning seems to be suitable in order to gather all the required data at same time, independent of lighting limitations, and providing better measurement accuracy[1]. The problem is that a methodology to classify and model the rail track from laser data did not exist up to now.

Computer vision techniques have been applied to extract some objects of the railway scene[2,3]. Some researches have focused on recognizing the bolts in the rails, and they face clear limitations to generate accurate measurements of rails and other objects.

Vertical dynamic model for the rail track and wagon interaction was researched and rail mode was proposed for predicting the dynamic responses of both the wagon and the rail track components[4]. Irregularities in wheel and/or rail generate sharp peak responses in the track–wagon system. Some irregularities cause periodic excitation whilst others cause non-periodic or localized excitation defined as impulse excitation in this paper. The periodic irregularities include the rail corrugations, the out-of-round wheels or the flat rounded wheels, and the non-periodic irregularities include the indentation on the railhead due to the spall or the defect of welded-joint and the dipped-joint.

Irregularities in the vertical profile and alignment can be modeled as a Gaussian random process. Power spectral density (PSD) of the irregularity is calculated and discussed. By analyzing the model, level-crossing properties as well as peak statistics are studied and compared with the observed data[5]. The deformation and pore-water pressure response within peat foundations are below three different railway embankments in response to cyclic heavy axle loading[6]. Wireless network structure was proposed with differential GPS and GSM[7]. Fast surges can cause many faults and outages on traction system. The identification of the reason of voltage disturbances (par-
particularly over-voltages) in traction system is of considera-
table importance[7]. A two-dimensional finite/infinite ele-
ment model with plane strain condition for railway track
was analyzed, and the vertical displacement, velocity, and
accelerations of track vibrations were examined by chang-
ing the values of ballast layer stiffness. The results show
that as the rail bed modulus or stiffness increases, the
acceleration of track vertical vibration increases, but the
vertical vibration velocity of track, the induced ground
displacement, velocity, and acceleration decreases[8]. A
MCDA method based on "multi-criteria analysis" with
GIS support for optimizing the choice of the corridors/line
of "high speed rail" (HRS)[9] safety system that will sole-
ly depend on train-based sensors and communication
device that can coexist with CBTC/PTC systems for
broken rail detection is provided[10]. Temperature force
and vehicle load can cause the continuous welded rail
track to buckle the influence of the lateral and longitudinal
ballast resistance, one of important factors to calculate the
critical values of the track using special finite element
program. Also, the sensitivity of the track irregularities
such as the alignment defect and the gauge irregularity are
investigated[11]. The practical monitoring of wheel de-
ficts for trains could be done through track mounted sen-
sors and the measured data are processed by an advanced
calculation program before being combined with the iden-
tification tag of a locomotive or a coach. This technique is
employed by existing condition-monitoring systems and
determines precisely which part of the train is
faulty/damaged and to what extent. Some of these wayside
monitoring devices have encouraged the adoption of con-
dition-based maintenance thereby saving the industry
valuable time and costs. Sensors can also be mounted on
the rolling stock in order to monitor the condition of the
railway vehicle infrastructure. So modern rolling stock is
fitted with high-capacity communication buses and multi-
ple sensors, which will results in the potential for ad-
vanced processing of collected data. This approach re-
quires intelligent image acquisition and analysis systems
which are capable of processing large amounts of data and
various ongoing research projects are tackling this task.
This paper is an attempt to collate and critically appraise
the techniques used for condition monitoring of railway
vehicle dynamics[12]. Quats are associated with high
frequency vibrations of the wheel-rail system and can be
registered using axle box acceleration (ABA) measure-
ments. In this paper a three-dimensional finite-element
(FE) model is proposed to capture the dynamic features of
the ABA related to squats in the high frequency range.
The FE model is validated relying on a set of real-life
ABA measurements at two characteristic rail surface de-
fects (light and severe squats), located in a section of the
railway network in Assen, Netherlands. The FE model
managed to properly capture the dynamic features in the
range of frequencies up to 2,000Hz[13]. An integrated
model called DARTS (Dynamic Analysis of Railway
Track Structures) has been applied for evaluating car body
accelerations, track deflections and wheel/rail forces
which are acquired from the passage of a Thalys high-
speed train, traveling on a conventional ballasted track or
non-conventional embedded rail structure[14]. The dy-
namic component of vertical wheel–rail contact forces, as
generated by irregularities in track geometry (longitudinal
level, isolated defects, insulated joints, rail corrugation,
switches & crossings, etc) and track stiffness (transition
zones, hanging sleepers, culverts, etc), is an important

II. STRUCTURE OF PROPOSED VISION SYSTEM FOR
DATA ACQUISITION

A. the structure of Data Acquisition system

The chapter will demonstrate some issues of design and
modeling of a part of a modern vision system for a rail
transport. This vision system is intended for capturing the
rails and wagon gesture, and it consists of the micro-
controllers, the developed software, the vision capturing
system, sensor system and GPS is shown in Figure1.

B. the installation location of Data Acquisition system

The proposed system is located in the train's operator
cabin near the front. When the train is running, data acquisi-
tion start operating. The installation is shown in Figure3.
III. RAIL TRACK DETECTION AND RADIUS FETCH

A. Image Segmentation

A simplified PCNN (pulsed coupled neural network) model called root mean square of gray-scale threshold pulse coupled neural network (RMS-PCNN) is applied for image segmentation[17]. The simplified PCNN model of neuron is shown in Figure 4.

\[ F_{i,j} = S_{i,j} \]

Each neuron is connected with the linking neurons. The linking output is based on the gray scale levels of the neurons in the linking field, as follows:

\[ L_{i,j} = \sum_k M_{k,j} S_k \]

where \( G \) is the linking matrix of neuron \( N_{i,j} \) which can be \( 3 \times 3 \) or \( 4 \times 4 \) linking field. Figure 5 shows a \( 3 \times 3 \) linking field.

The linking inputs are biased and then multiplied with the feeding input to form the internal activity \( U(i,j) \):

\[ U_{i,j} = F_{i,j}(1 + \beta^* L_{i,j}) \]

The pulse generator of the neuron consists of a step function generator and a threshold signal generator. At each firing step, the neuron output \( Y_{i,j} \) is set to 1 when the internal activity \( U_{i,j} \) is greater than the threshold \( \theta \), otherwise the output is set to 0, as the following:

\[ Y_{i,j} = \text{step}[U_{i,j} - \theta] = \begin{cases} 1, & U_{i,j} > \theta \\ 0, & \text{others} \end{cases} \]

where \( \theta \) is the threshold related to the gray scale statistics of the image. Just as the following:

\[ \theta = \sqrt{\frac{\sum_{i,j} S_{i,j}^2}{m \times n}} \]

where \( I \) is the \( m \times n \) gray-scale-matrix of the image, and \( m \) and \( n \) are the number of the pixel of the rows and columns in the image respectively.

B. coupled map lattice

A coupled map lattice (CML) is a dynamical system that models the behavior of non-linear systems (especially partial differential equations)[18]. They are predominantly used to qualitatively study the chaotic dynamics of spatially extended systems. Features of the CML are discrete time dynamics, discrete underlying spaces (lattices or networks), and real (number or vector), local, and continuous state variables. Studied systems include populations, chemical reactions, convection, fluid flow and biological networks. More recently, CMLs have been applied to computational networks identifying detrimental attack methods and cascading failures including image segmentation. A overall map is established with gray-level. Four pixels neighbored \( x_{ij} \) couple with \( x_{ij} \) shown in Eq6.

\[ X_{n+1}(i, j) = (1 - \xi) f_n(i, j) + \frac{\xi}{4} \left[ f_n(i-1, j) + f_n(i+1, j) + f_n(i, j-1) + f_n(i, j+1) \right] \]

where \( f_n(i, j) = f_n(i, j) + f_n(i+1, j) + f_n(i, j-1) + f_n(i, j+1) \)

A CML generally incorporates a system of equations (coupled or uncoupled), a finite number of variables, a global or local coupling scheme and the corresponding coupling terms. The underlying lattice can exist in infinite dimensions. Mappings of interest in CMLs generally demonstrate chaotic behavior. Logistic map is used widely in coupled map lattice shown in Eq7.

\[ x_{n+1} = a \times x_n \times (1 - x_n) \]

In Eq8, the next \( x \) is split as threshold 0.5.

\[ x_{n+1} = \begin{cases} a \times \sqrt{x_n} \times (1 - \sqrt{x_n}), x_n \geq 0.5 \\ a \times \sqrt{x_n} \times (1 - \sqrt{x_n}), x_n < 0.5 \end{cases} \]

Compared with coupled map lattice and directed binary, the rail-track is segmented obviously from rubble bed shown in Figure 6.

C. Rail track Detection

After image binary, a box filter is applied for filter discrete pixels and the box size varies dynamically according to the pixels in the area. Edge is founded, then binary search tree is established from the bottom of image. Rail tracks can be segmented from rubble bed. According to the rail’s characteristic, the points whose color is black are continuous, and the others are distributed. Box filter whose size is adaptive is used to filter points in sized box less than \( 3 \times 3 \). The rail can be segmented from rubble bed significantly as shown in Figure 7. After edge detection, Bi-
nary tree is searched for finding rail tracks as shown in Figure 8.

According to the rail track's characteristic, the distance between the two rail tracks is invariable (omitted extended width in the curve), this can be a criterion for view morphing to determine transform matrix. Because the camera is fixed in the front of operate cabin, assumed it is paralleled to rail tracks at the nearest point. By perspective, figure can be obtained. then the radius can be fetched by analysis of regression as shown in Figure 9.

![Figure 8. Railtrack extraction by binary tree searching](image1)

![Figure 9. Railtracks by perspective and radius fetch](image2)

IV. UKF-SVD FOR GYROSCOPE DATA

A. UKF-SVD introduction

UKF (unscented Kalman Filter) is widely used for state estimation. But UKF often encounters the ill-conditioned problem when solving the square root of the co-variance matrix in practice. The improved UKF based on SVD (singular value decomposition) is proposed focus on sigma samples [20, 21, 22]. The standard UKF is as follows:

\[
x_k = f(x_{k-1}) + \omega_k
\]

\[
y_k = h(x_k) + v_k
\]

where, \(x_k \in \mathbb{R}\) is the states vector, and \(y_k \in \mathbb{R}\) are the input and output vectors at time instant \(k\), respectively. \(v_k\) and \(\omega_k\) are the process noise and measurement noise such that

\[
E[v_k] = 0, E[\omega_k] = 0
\]

\[
E[\omega_k \omega_k^T] = R, \delta_{ij}, E[v_k v_k^T] = Q, \delta_{ij}
\]

Here supposed that \(\omega_k, v_k, x_k\) are not correlated to each other. Where \(\delta_{ij}\) is Kronecker-\(\delta\) function. UKF algorithm for the associated noisy nonlinear system is described as follows:

1) Initialization

\[
\hat{x}_0 = E[x_0], P_0 = E[(x - \hat{x}_0)(x - \hat{x}_0)^T]
\]

\[
W_{\omega}^m = \frac{\Delta}{n + \Delta}
\]

\[
W_{\omega}^c = \frac{\Delta}{n + \Delta} + (1 - \alpha^2 + \beta)
\]

\[
W_{v}^c = W_{\omega}^c = \frac{1}{2(\Delta + \Delta)}\]

2) Sigma points

UKF often encounters the non positive definite problem when solving the square root of the co-variance in practice. Therefore, unscented Kalman filter based on SVD overcome this problem for computing sigma points [20, 21].

\[
P_{k-1} = U_{k-1} \Sigma_{k-1} U_{k-1}^T
\]

\[
\hat{X}_{k} = [\hat{X}_{k-1}, X_{k-1} + \sqrt{m + \Delta} \times U_{k-1} \times \sqrt{S_{k-1}}]
\]

\[
X_k = 1 - \sqrt{m + \Delta} \times U_{k-1} \times \sqrt{S_{k-1}}\]

3) time update

\[
X_{k|k-1} = f(X_{k-1}), \hat{x}_{k|k-1} = \sum_{i=0}^{2m} W_{i}^m X_{i,k-1}
\]

\[
P_{k|k-1} = \sum_{i=0}^{2m} W_{i}^m (X_{i,k|k-1} - \hat{x}_{i,k|k-1})(X_{i,k|k-1} - \hat{x}_{i,k|k-1})^T + Q_k
\]

4) measure update

\[
y_{i,k|k-1} = h(X_{i,k|k-1}), y_k = \sum_{i=0}^{2m} W_{i}^m y_{i,k|k-1}
\]

\[
P_y = \sum_{i=0}^{2m} W_{i}^m (y_{i,k|k-1} - \hat{y}_k)(y_{i,k|k-1} - \hat{y}_k)^T + R_k
\]

5) filter update

\[
P_y = \sum_{i=0}^{2m} W_{i}^m (X_{i,k|k-1} - \hat{x}_{i,k|k-1})(X_{i,k|k-1} - \hat{x}_{i,k|k-1})^T
\]

\[
K_k = P_{y} P_{y}^{-1}
\]

\[
\hat{x}_k = \hat{x}_{k|k-1} + K_k (y_k - \hat{y}_k)
\]

\[
P_k = P_{k|k-1} - K_k P_{y} K_k^T
\]

B. Data Processing

Data of gyroscope and accelerometer are collected by UART with fixed Bps. In fact, the transmit speed varies from 30 to 120 per second. For acquiring same sampling scope sensor of 12,000 data points, and the sampling frequency is 120Hz.

The measure points are selected as input for UKF-SVD, and the estimated points are treated as real gesture of wagon vibration. Each 7000 points are selected for each filtering by UKF based on SVD include 1000 points which are selected for overlap. The real wagon gesture is shown in Figure 10, and the error limit is in 10^-3. From the results of radius fetch the line track or arc track can be distinguished and radius of arc can be calculated. Looking up the radius record table, the corresponding threshold in gyroscope signal can be selected. In line track and arc track, when exceed the threshold as Eq. 16. Eq. 17 shows the super elevation related to speed and radius.

\[
\begin{align*}
\text{< threshold 1, } R &= \infty, \text{ Line} \\
\text{< threshold 2, } R &< R_2, \text{ Arc 1} \\
\text{< threshold 3, } R_2 &< R < R_3, \text{ Arc 2} \\
\text{......} \\
E &= \frac{7.6V^2}{R}
\end{align*}
\]

Where \(R\) is radius of curve or arc with unit meter, and \(V_{\text{max}}\) is the max run speed of the train at unit km/h.
V. CONCLUSION

Vision system consists of vision capturing system, sensor system and GPS, is intended for capturing the rails and wagon gesture. RMS-PCNN is used for image binary in a sor system and GPS, is intended for capturing the rails and improved couple map lattice with asymmetric is used for perspective, radius is fetched by regression.

The vibration signal is filtered by UKF-SVD can reflect the wagon gesture status, and Cholesky is replaced by SVD in UT(unsecented transform), which can solve negative definite matrix caused by co-variance matrix on account of calculation error and round-off error. Compared to threshold and super elevation which are obtained from the standard for constructional quality acceptance of railway track engineering, the rail defects can be found while exceeding the maximum or less than minimum of super elevation.

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