Recognition of Cross Profiles of Roadbed Based on Polygonal Representations

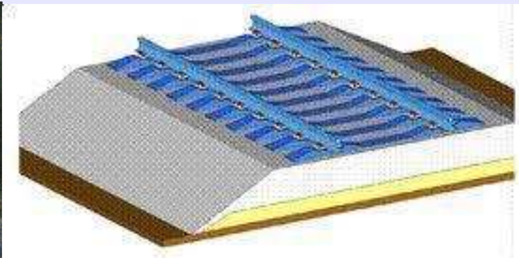
Andrey G. Bronevich[1], Alexander E. Lepskiy[1], Vladimir I. Umansky[2], Dmitry A. Yakushev[2]

[1] National Research University "Higher School of Economics", Moscow, Russia

[2] JSC Intechgeotrans, Moscow, Russia

The 5^{th} International Conference on Pattern Recognition and Machine Intelligence, December 10 - 14, 2013, Kolkata, India

Nowadays there are several program systems that allow to monitor automatically railway roads. These systems give possibility to find defects linked with the track structure, gabarite dimensions, rail cross profiles, etc.

Problem

The development of roadbed profiles recognition system that is then used for detection of roadbed defects, like non-normative breadth of ballast shoulder, non-normative breadth of roadbed shoulder, places of oversized angles of slope.

Outline of presentation

1. Data description: cross profiles of roadbed
2. Recognition of road bed profiles based on their polygonal representations
    - problem statement
    - comparison of polygonal representations based on invariants
    - comparison of polygonal representations by norms on the curve space
3. Selection of the most preferred profile
4. Summary and conclusion

Data description: cross profiles of roadbed

This problem can be solved by comparing the measured profile with the normative profile according to the design decision. If the design decision is not known we need to recognize the measured profile using the set of all possible etalon profiles. In this case we have the set of etalon profiles that correspond to different types of roadbed that can be classified as ditch cuts, embankments, tunnels, etc.

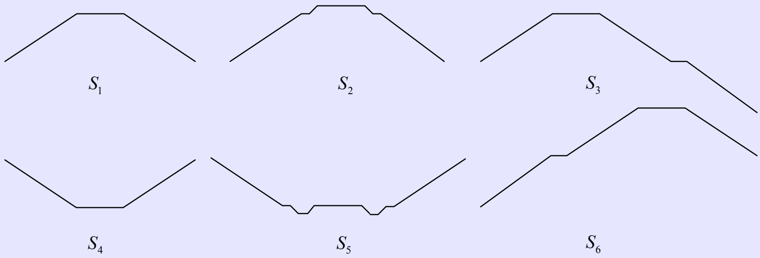


Fig. Examples of etalon profiles.

Fig. Laser scanner on train (http://nipistroytek.ru/).

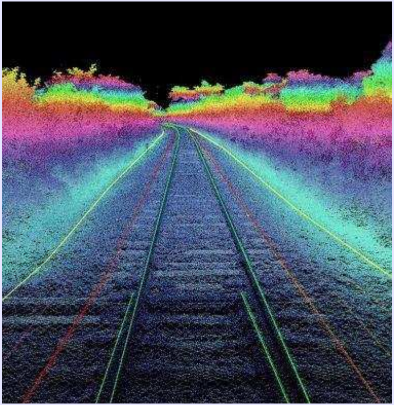


Fig. Points cloud (http://www.artescan.net/).

The results of laser scanning of railway roadbed are the data for recognition and classification.

Fig. Real initial profile of railways roadbed.

Data

- points cloud;
- the 2000-3000 points are in the initial profile of railways roadbed;
- the 6-10 classes of different normative profiles;
- the profiles data are normalized with respect to scale and rotation.

Requirements

- on-line processing on the high speed of movement scanner;
- there are large and lot distortions of profiles.

Feature points of roadbed profile

The analysis of the cross profile of the roadbed assumes that we need to extract feature points, whose positions determine the basic characteristics of the roadbed. The feature points are points corresponding to edges of upper and lower surfaces of embankment (ditch cut) of the roadbed and the ballast section. These points can be extracted by the statistical method of recovering profile.

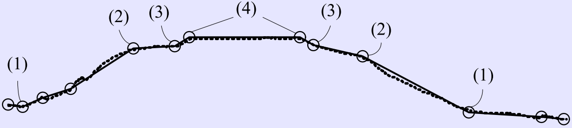


Fig. Profile, polygonal representation and feature points: (1) the edge points of the bottom surface of the embankment edge, (2) the edge points of the upper surface of the embankment edge, (3) the edge points of lower surface of ballast section; (4) the edge points of the top surface edge ballast.

Recognition of road bed profiles based on their polygonal representations

The problem statement

Given etalon profiles $S_1, ..., S_N$ of the roadbed. Each profile S_j, $j = 1, ..., N$, is defined by a polygonal representation $S_j = \{\mathbf{s}_1^{(j)}, ..., \mathbf{s}_{n_j}^{(j)}\}$, where $\mathbf{s}_i^{(j)} = (u_i^{(j)}, v_i^{(j)})$, $i = 1, ..., n_j$, $j = 1, ..., N$, are vertices of the corresponding polygon. We assume that $u_1^{(j)} < u_2^{(j)} < ... < u_{n_j}^{(j)}$. It is necessary to recognize the measured profile that is also described by the polygonal representation $X = \{\mathbf{x}_1, ..., \mathbf{x}_m\}$, where $\mathbf{x}_i = (x_i, y_i)$, $i = 1, ..., m$, and $x_1 < x_2 < ... < x_m$.

The classification problem consists in finding etalon profile S_j that is similar to the measured profile X according to the chosen distant function. After that it is possible to compute the important characteristics of X like the height of embankment or the depth of ditch cut, and others.

The comparison of polygonal representations based on invariants

Let $X^{(p,l)} = \{\mathbf{x}_i\}_{i=p}^{p+l-1}$ be a part of X that consists of l points. We will characterize any such representation $Y = X^{(p,l)}$ by the following vectors of features that are invariant w.r.t. the choice of coordinate system:

1. $\mathbf{r}(Y) = (r_i(Y))_{i=1}^{l-2}$, where $r_i(Y) = |\mathbf{r}_{i+2} - \mathbf{r}_{i+1}|/|\mathbf{r}_{i+1} - \mathbf{r}_i|$ is the ratio of lengths of two neighboring segments;
2. $\beta(Y) = (\beta_i(Y))_{i=1}^{l-2}$, where $\beta_i(Y)$ is the angle between neighboring segments $[\mathbf{r}_i, \mathbf{r}_{i+1}]$ and $[\mathbf{r}_{i+1}, \mathbf{r}_{i+2}]$;
3. $\sigma(Y) = (\sigma_i(Y))_{i=1}^{l-2}$, where $\sigma_i(Y)$ is the sign of angle between neighboring segments $[\mathbf{r}_i, \mathbf{r}_{i+1}]$ and $[\mathbf{r}_{i+1}, \mathbf{r}_{i+2}]$.

Let $X_1^{(p_1,l_1)}$ and $X_2^{(p_2,l_2)}$ be parts of polygonal representations. Then they are called *comparable* if $l_1 = l_2$ and $\sigma\left(X_1^{(p_1,l_1)}\right) = \sigma\left(X_2^{(p_2,l_2)}\right)$.

Let $G_0 = \left\{ \left(X^{(p,l)}, S_k^{(m,l)} \right) \right\}$ be the set of comparable parts of polygonal representations of the measured profile and etalon profiles. Then we can compute the similarity of comparable representations using the Euclidean metric

$$\rho\left(X^{(p_1,l)}, S_k^{(p_2,l)}\right) = \sqrt{\left\| \mathbf{r}\left(X^{(p_1,l)}\right) - \mathbf{r}\left(S_k^{(p_2,l)}\right) \right\|^2 + w \left\| \beta\left(X^{(p_1,l)}\right) - \beta\left(S_k^{(p_2,l)}\right) \right\|^2}.$$

Let

$$\Upsilon_k = \left\{ \rho\left(X^{(p_1,l)}, S_k^{(p_2,l)} \right) : \left(X^{(p_1,l)}, S_k^{(p_2,l)} \right) \in G_0 \right\}, k \in \{1, ..., N\},$$

be the ordered set of distances, where $\rho\left(X^{({p_1}^{(1)},l^{(1)})}, S_k^{({p_2}^{(1)},l^{(1)})} \right)$ is after $\rho\left(X^{({p_1}^{(2)},l^{(2)})}, S_k^{({p_2}^{(2)},l^{(2)})} \right)$ if $p_1^{(1)} > p_1^{(2)}$ or $\left(p_1^{(1)} = p_1^{(2)} \right) \wedge \left(l^{(1)} \geq l^{(2)} \right)$.

Let G_1 be a set of pairs that correspond to the minima in vectors $\Upsilon_k = \{\rho_i\}$, $k = 1, ..., N$. For each pair $\left(X^{(p,l)}, S_k^{(m,l)}\right) \in G_1$ we normalize polygonal representations X and S_k by finding the coordinate system that corresponds to similar parts $X^{(p,l)}$ and $S_k^{(m,l)}$. This leads to the following optimization problem

$$\left\| AX^{(p,l)} - S_k^{(m,l)} - \mathbf{b} \right\|^2 \to \min$$

w.r.t. orthogonal transformation A and vector $\mathbf{b} \in \mathbb{R}^2$. After that we can compute the normalized representation of X by the formula

$$\tilde{X} = AX^{(p,l)} - \mathbf{b}.$$

After that we should find the best normalization among possible ones with help of distance images between the normalized profile $\tilde{X}$ and the etalon profile S_k. In this case polygons $\tilde{X}$ and S_k are depicted as binary images. Let $Y = \{y_{i,j}\}_{N_1 \times N_2}$, where $y_{i,j} \in \{0, 1\}$, be a binary image. Then the distance image is the matrix $Y^* = \{y^*_{i,j}\}_{N_1 \times N_2}$ computed by

$$y^*_{i,j} = \min_{(k,m) | y_{k,m} = 1} \sqrt{(i-k)^2 + (j-m)^2}.$$

Let Y_1 and Y_2 be polygons and let ${Y_1}^*$ and ${Y_2}^*$ be the corresponding distance images. Then the closure between Y_1 and Y_2 can be measured by

$$\mu(Y_1, Y_2) = \frac{\|Y_1^* - Y_2^*\|}{\max\{\|Y_1^*\|; \|Y_2^*\|\}}.$$

Let $\tilde{X}_k$ be the best normalization of X w.r.t. etalon image S_k providing the minimum of μ. Then the classification rule can be defined as: the measured profile X corresponds to the etalon S_m if $\mu(\tilde{X}_m, S_m) \leq \mu(\tilde{X}_k, S_k)$, $k = 1, ..., N$.

Example of comparison of polygonal representation and etalon

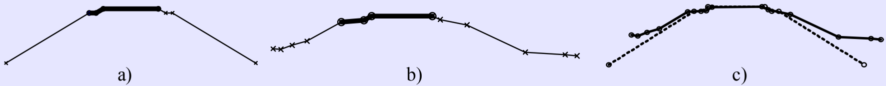


Fig. Parts of polygonal representations: a) optimal $S_2^{(m,l)}$ (bold line); b) optimal $X^{(p,l)}$ (bold line); c) S_2 and $\tilde{X}_2$.

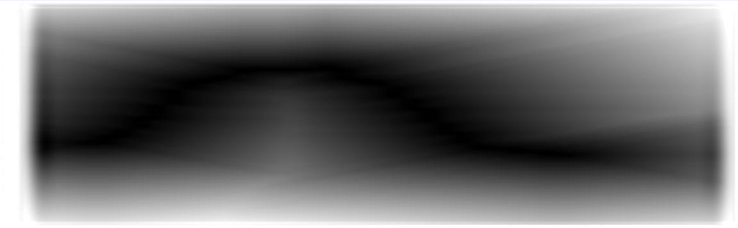


Fig. Visualization of distance image of profile.

The comparison of polygonal representations by norms on the curve space

Any polygon can be considered as a piecewise linear function. There is a possibility for comparing polygons using a norm defined in a space $C_p^w[a,b]$ of continuous functions on $[a,b]$ with the norm

$\|f\|_{w,p} = \left(\int_a^b w(t)|f(t)|^p dt\right)^{\frac{1}{p}}$, $1 \leq p < \infty$, $\|f\|_{w,\infty} = \max\limits_{t\in[a,b]} w(t)\,|f(t)|$.

Let us assume that we can detect feature points $\mathbf{x}^{(0)} = (x^{(0)}, y^{(0)})$, $\mathbf{x}^{(1)} = (x^{(1)}, y^{(1)})$ of the measured profile X and corresponding points $\mathbf{s}^{(0)} = (u^{(0)}, v^{(0)})$, $\mathbf{s}^{(1)} = (u^{(1)}, v^{(1)})$ in the etalon representations.

Using these points we can produce the normalizations $\hat{S} = \{\hat{\mathbf{s}}_1, ..., \hat{\mathbf{s}}_n\}$ and $\hat{X} = \{\hat{\mathbf{x}}_1, ..., \hat{\mathbf{x}}_m\}$ of the etalon and the measured profiles as follows:

$$\hat{u}_j = u_j - \tfrac{1}{2}(u^{(0)} + u^{(1)}), \hat{v}_j = v_j - \tfrac{1}{2}(v^{(0)} + v^{(1)}), \quad j = 1, ..., n,$$

$$\hat{x}_i = \frac{\left\|\mathbf{s}^{(0)} - \mathbf{s}^{(1)}\right\|}{\left\|\mathbf{x}^{(0)} - \mathbf{x}^{(1)}\right\|}\left(x_i - \tfrac{1}{2}(x^{(0)} + x^{(1)})\right), \hat{y}_i = \frac{\left\|\mathbf{s}^{(0)} - \mathbf{s}^{(1)}\right\|}{\left\|\mathbf{x}^{(0)} - \mathbf{x}^{(1)}\right\|}\left(y_i - \tfrac{1}{2}(y^{(0)} + y^{(1)})\right),$$

$i = 1, ..., m$, where $\hat{\mathbf{s}}_j = (\hat{u}_j, \hat{v}_j)$, $j = 1, ..., n$; $\hat{\mathbf{x}}_i = (\hat{x}_i, \hat{y}_i)$, $i = 1, ..., m$.

Example of normalization of polygonal representation

The result of the normalization of polygonal representation of the measured profile and one of the reference profiles from the database is shown in Figure.

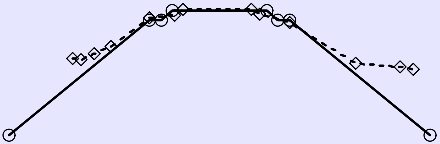


Fig. The normalization of polygonal representation of the measured profile and one of the reference profiles from the database.

For notation simplicity, let us assume that polygonal representations X and S are normalized.

The distance between X and S can be computed by the algorithm:

1. compute the union of sequences $\{x_i\}_{i=1}^m$ and $\{u_j\}_{j=1}^n$ such that $Z = \{z_k\}_{k=1}^l = \{x_i\}_{i=1}^m \cup \{u_j\}_{j=1}^n$: $z_1 < z_2 < ... < z_l$;
2. the values of piecewise linear functions of profiles X and S are computed for any point $z_k \in Z$ by formula (filling of data gaps by linear interpolation)

$$\tilde{y}_i = \begin{cases} y_i, & \text{if } z_k = x_i, \\ l(z_k|\mathbf{x}_i, \mathbf{x}_{i+1}), & \text{if } x_i < z_k < x_{i+1}, \\ l(z_k|\mathbf{x}_1, \mathbf{x}_2), & \text{if } z_k < x_1, \\ l(z_k|\mathbf{x}_{m-1}, \mathbf{x}_m), & \text{if } z_k > x_m \end{cases} \quad \tilde{v}_i = \begin{cases} v_j, & \text{if } z_k = u_j, \\ l(z_k|\mathbf{s}_j, \mathbf{s}_{j+1}), & \text{if } u_j < z_k < u_{j+1}, \\ l(z_k|\mathbf{s}_1, \mathbf{s}_2), & \text{if } z_k < u_1, \\ l(z_k|\mathbf{s}_{n-1}, \mathbf{s}_n), & \text{if } z_k > u_n, \end{cases}$$

where $l\,(t|\mathbf{a}, \mathbf{b})$ be a linear function whose graph passes through points $\mathbf{a}$ and $\mathbf{b}$. We get a profiles $X = \{\mathbf{x}_1, ..., \mathbf{x}_l\}$ and $S = \{\mathbf{s}_1, ..., \mathbf{s}_l\}$, where $\mathbf{x}_i = (z_i, \tilde{y}_i)$, $\mathbf{s}_i = (z_i, \tilde{v}_i)$;

3. the transformations made in 1) and 2) allow us to compute the distances using formulas

$$d_{p,w}(X,S) = \sqrt[p]{\sum_{i=1}^{l-1} w_i |\tilde{y}_i - \tilde{v}_i|^p (z_{i+1} - z_i)}, \quad 1 \leq p < \infty,$$

$$d_{\infty,w}(X,S) = \max_{1 \leq i \leq l} w_i \left|\tilde{y}_i - \tilde{v}_i\right|.$$

The choice of w_i can decrease the influence of points with a small informativity that are located far from the track.
The metric d_1 is proportional to quantity of work which must be made to correct of roadbed.

Example of comparison of polygonal representation and etalon

Let we apply metrics $d_1(X, S_k)$ and $d_{1,w}(X, S_k)$ with $w_i = w_0\left(1 + \left|\frac{1}{2}l - i\right|^4\right)^{-1}$, $k = 1, ..., 6$, to the measured profile X and etalon profiles as on figures. In this case the corresponding distances are given in Table.

Table. Values of distances $d_1(X, S_k)$ and $d_{1,w}(X, S_k)$ $k = 1, ..., 6$.

	S_1	S_2	S_3	S_4	S_5	S_6
$d_1(X, S_k)$	41,5	28,9	78,8	105,9	77,5	157
$d_{1,w}(X, S_k)$	1,28	0,38	0,59	4,63	1,28	1,18

Thus, the etalon profile S_2 by both metrics has better fitted for X.

Selection of the most preferred profile

We say that the etalon profile S_i is more preferable than the profile S_j ($S_i \succ S_j$) for the classification of the measured profile X if $d(X, S_i) < d(X, S_j)$. If we have $d(X, S_i) = d(X, S_j)$ then we say that these profiles have the same preferences and denote it by $S_i \simeq S_j$.

It is possible to use the threshold comparison to enhance the robustness of the comparison procedure:

$$S_i \succ S_j \quad \text{if} \quad d(X, S_i) \leq d(X, S_j) - \varepsilon$$

and

$$S_i \simeq S_j \quad \text{if} \quad |d(X, S_i) - d(X, S_j)| < \varepsilon,$$

where $\varepsilon > 0$ is a threshold value.

Then we have the following ordering of etalon profiles by preference in according to the metric d_1:

$$S_2 \succ S_1 \succ S_5 \succ S_3 \succ S_4 \succ S_6.$$

We have the following ordering at 5% threshold comparison (i.e. ε is equal 5% from the $\max_k d_1(X, S_k) - \min_k d_1(X, S_k)$):

$$S_2 \succ S_1 \succ S_5 \simeq S_3 \succ S_4 \succ S_6.$$

The ordering of etalon profiles is different for the specified weighted metrics $d_{1,w}$:

$$S_2 \succ S_3 \succ S_6 \succ S_1 \simeq S_5 \succ S_4$$

for the nonthreshold comparison and

$$S_2 \simeq S_3 \succ S_6 \simeq S_1 \simeq S_5 \succ S_4$$

for 5% threshold comparison.

Summary and conclusion

- The studies have shown the effectiveness of the proposed scheme in general classification profiles of railways roadbed.
- The every from two considered approaches has own advantages and disadvantages. For example, the first approach (with help invariants) is more universal methods than the second approach.
- But the edge points of the upper surface of the edge of ballast section should be allocated accurately in second approach.
- The second approach (with help of metric) allows us to estimate the volume of work that must be performed to correction of ballast section.
- The both schemes of classification may be performed in real time.

Thanks for you attention

brone@mail.ru
alex.lepskiy@gmail.com
umanvi@yandex.ru
d.yakushev@gismps.ru