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Curved planar reformation of CT spine images

Tomaž Vrtovec

University of Ljubljana, Faculty of Electrical Engineering, Tržaška 25, SI-1000 Ljubljana, Slovenia
E-pošta: tomaz.vrtovec@fe.uni-lj.si

Abstract. Traditional techniques for visualizing anatomical structures are based on planar sections from volume images, like images obtained by computed tomography (CT) or magnetic resonance imaging (MRI). However, planar slices taken in the coordinate system of the 3D image often do not provide sufficient or qualitative enough diagnostic information. The reason is that because planar slices do not follow curved anatomical structures (e.g. arteries, colon, spine, etc.), not all important details can be shown simultaneously. For better visualization of curved structures, reformatted images in the coordinate system of a structure must be created (an operation called curved planar reformation). In this paper we focus on automated curved planar reformation (CPR) of CT spine data. The obtained spine-based 3D coordinate system is determined by the natural curvature of the spine, described by a curve that is parameterized by a polynomial model. The model is optimized to fit the curvature of the spine basing on the values of a pre-calculated distance map. The first coordinate is defined by the resulting spine curve, while the other two coordinates are defined by the natural rotations of the vertebrae around the spine curve. The proposed approach benefits from reduced structural complexity in favor of improved feature perception of the spine, and is not only important for extracting diagnostically important images, but also for easier navigation, manipulation and orientation in 3D space, which is helpful for morphometric analysis, automated image analysis (e.g. segmentation), and normalization of spine images.

Keywords: visualization, curved planar reformation, spine, computed tomography (CT)

Vzorčenje CT slik hrbtenice po ukrivljeni ploskvi

Povzetek. Pregledovanje anatomskih struktur ponavadi temelji na prikazu ravninskih prerezov prostorskih slik, pridobljenih z različnimi slikovnimi tehnikami, kot sta npr. računalniška tomografija (CT) ali magnetna resonanca (MRI). Ravninski prerezi so postavljeni v koordinatni sistem, ki ga določa 3D slika, zato velikokrat ne vsebujejo dovolj informacije oz. informacije zadovoljive kakovosti. Razlog je v tem, da ravninski prerezi ne sledijo ukrivljenosti anatomskih struktur (npr. arterije, debelo črevo, hrbtenica itd.), posledično pa vsa pomembna področja ne morejo biti hkrati prikazana na posameznem prerezu. Ukrivljene anatomske strukture prikažemo tako, da jih postavimo v koordinatni sistem strukture, kar storimo z operacijo vzorčenja po ukrivljeni ploskvi (CPR). V pričujočem delu se osredotočamo na avtomatsko CPR CT slik hrbtenice. 3D koordinatni sistem hrbtenice je določen z naravno ukrivljenostjo hrbtenice, ki ga opisuje krivulja v obliki polinomskega modela. Model se optimalno prilega ukrivljenosti hrbtenice na podlagi predhodno izračunanega polja razdalj. Smer prve koordinate je določena s krivuljo hrbtenice, preostali dve koordinatni smeri pa sta določeni z naravno rotacijo vretenc okoli te krivulje. Predlagani postopek zmanjša strukturno kompleksnost slike, izboljša zaznavanje bistvenih značilnosti hrbtenice ter omogoča pridobivanje informacijsko bogatih diagnostičnih slik. Poleg tega je pomemben tudi za lažjo navigacijo, manipulacijo in orientacijo v 3D prostoru, kar je pomembno pri morfometrični analizi, avtomatski analizi slik (npr. razčlenjevanje) in normiranju slik hrbtenice.

Ključne besede: vizualizacija, vzorčenje po ukrivljeni ploskvi, hrbtenica, računalniška tomografija (CT)

1 Introduction

Traditional techniques for visualizing anatomical structures are based on planar sections from volume images, like images obtained by computer tomography (CT) or magnetic resonance imaging (MRI). Three-dimensional (3D) rendering removes the constraints of two-dimensional (2D) imaging, allowing anatomy to be

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viewed from multiple angles and thus providing an improved view of complex 3D anatomical structures. However, planar slices taken in the coordinate system of the 3D image often do not provide sufficient or qualitative enough diagnostic information. Orientation and correct selection of a structure of interest can be difficult in the standard reformation (i.e. axial, sagittal and coronal). The reason is that because planar slices do not follow curved or tubular anatomical structures (e.g. arteries, colon, spine, etc.), not all important details can be shown simultaneously in any planar slice. For better visualization of curved structures, reformatted images orthogonal or tangent to a curve along a tortuous 3D structure, i.e. images in the coordinate system of the structure, must be created. This process is called curved planar reformation (CPR) and can be used to overcome the presented shortcomings, i.e. not being able to display the whole course of a tubular structure within a single image.

CPR has been widely used for visualization of blood vessels and evaluation of vascular abnormalities in the field of CT angiography. Different CPR methods for the visualization of blood vessels were described and evaluated by Kanitsar et al. [1], who also proposed a number of enhancements and introduced two advanced CPR methods in [2]. In [3], a method capable of automatically producing and interactively displaying CPR images of blood vessels was presented. Saroul et al. [4] extended the notion of CPR to extraction of free form surfaces and mentioned the possibility of free form surfaces to follow non-tubular and irregular anatomical structures. Recently, CPR techniques have been applied to other structures of interest. The authors in [5] showed that the generation of CPR images could be used for evaluating pancreatic and peripancreatic diseases. Common to all of the reported methods is that the most important issue for CPR is the appropriate estimation of the centerline of a tubular structure. Besides in angiography [6, 7], it is also investigated in the field of virtual colonoscopy [8, 9] and bronchoscopy [10].

In analysis of spinal structures, a model of the curvature of the spinal column commonly takes into account the spatial relationship between vertebrae and therefore it is likely that it will assist high level image analysis (e.g. spine segmentation). Ghebreab et al. [11] stacked models of single vertebrae to construct a model at the level of the spine which was used to assist segmentation. Determination of the spinal curvature was based on the assumption that the surface landmarks occur at approximately the same position on a vertebra and can be therefore connected by a curve. In [12], an a priori geometric model of the whole spine was presented. The model, based on simple cubic templates which parameters were given by statistical knowledge on a scoliotic population, was used to roughly estimate position and orientation of each vertebra. Different reformation approaches that refer to CT spine data have already been introduced and reported to be successful in assisting the evaluation of spine deformities. Roberts et al. [13] reformatted the image data perpendicular to the long axis of both the left and right neural foramen of the cervical spine segment. Congenital spine abnormalities were examined by Newton et al. [14], who showed that advanced imaging improves the identification of deformities that are difficult to interpret and understand by conventional imaging. Besides standard multiplanar they also manually generated curved multiplanar reformatted images that represented the whole spine on each image. Kaminsky et al. [15] proposed a protocol for spine segmentation composed of standard and newly developed interactive segmentation tools that were combined with data reformation. A 3D spline was placed through the centers of vertebrae that was directed either manually by determining centerlines on sagittal and coronal planes, or automatically by dropping spheres through the vertebral bodies or the spinal canal. In order to overcome the problems of orientation in the standard reformation, the initial image was reformatted in such a way that the center spline formed the center axis of the rotated images.

The motivation for the present work was to design, develop and test an automated CPR method for CT spine data with minimal human intervention. Our algorithm performs automatic extraction of the tubular structure that follows the vertebral bodies along the spinal column and delineates the natural curvature of the spine. It is designed to fit both the physiological curvature as well as pathological deformations (e.g. scoliosis) of the spine. The high level information gained from the centerline is then used to reformat the data. The curvature, characteristic of the spine, is not only important for extracting diagnostically important images, but also for easier navigation, manipulation and orientation in 3D space, and for easier identification of the marginal structures of the spine. The ability to display the whole spinal column length within a single image makes the inspection of images quicker and more precise. The proposed method may provide additional support in the field of morphometric analysis (e.g. measuring dimensions of vertebral pedicles, vertebral foramens and spinal canal), automated image analysis (e.g. segmentation), and normalization of spine images.

2 Method

2.1 Polynomial model of spinal curvature

The proposed CPR transforms the image from its standard, image-based, to a spine-based coordinate system determined by the natural curvature of the spine. The spinal curvature can be described by a curve that passes through the centers of vertebral bodies. The curve is represented by a parametrical model, which is optimized to fit the distance map D, obtained by computing Euclidian distances from the edges of the bone structures. This task is facilitated by the fact that we are searching for edges that only roughly separate the bone structures from the other structures in the image. The obtained distances are positive inside and negative outside the bone structures. We exploit the anatomical fact that vertebral bodies are locally the largest bone structures along the spinal column, therefore the values of the distance map are expected to be the highest in geometrical centers of vertebral bodies and smoothly decrease by moving away from the centers.

The spinal curvature is described by a curve that is parameterized by a polynomial model. The curve $c(n) = (x(n),\ y(n),\ z(n))$ is represented by a set of samples $n = \{n_i;\ i = 1,2,...,N\}$ in 1D space that is continuously mapped to the 3D space in the coordinate system of the image, resulting in three univariate polynomial functions, each describing the course of one of the image coordinates (x, y, z):

$$x(n) = \left\{ x_i ; x_i = \sum_{k=0}^{K_x} b_{x,k} \frac{n_i^k}{\hat{b}_{x,k}} ; i = 1,2,...,N \right\}$$
$$y(n) = \left\{ y_i ; y_i = \sum_{k=0}^{K_y} b_{y,k} \frac{n_i^k}{\hat{b}_{y,k}} ; i = 1,2,...,N \right\} \qquad (1)$$
$$z(n) = \left\{ z_i ; z_i = \sum_{k=0}^{K_z} b_{z,k} \frac{n_i^k}{\hat{b}_{z,k}} ; i = 1,2,...,N \right\}$$

K_x, K_y and K_z are the degrees and $b_x = \{b_{x,k};\ k = 0,1,...,K_x\}$, $b_y = \{b_{y,k};\ k = 0,1,...,K_y\}$ and $b_z = \{b_{z,k};\ k = 0,1,...,K_z\}$ are the parameters of the polynomials $x(n)$, $y(n)$ and $z(n)$, respectively. The parameters are normalized over the curve domain, so that the modification of each parameter has the same impact on the variation of the curve:

$$\int_{n_1}^{n_N} \left| \frac{n^k}{\hat{b}_{<x,y,z>,k}} \right| dn = 1; k = 0,1,...,K_{<x,y,z>} \qquad (2)$$

The vertebral bodies, together with the intervertebral discs, form a tubular structure with a central axis that matches the spine curve. The size of the vertebral bodies, however, is not constant along the spinal column, so we parameterize the radius of the tubular structure similarly as the spine curve in Eq. (1), i.e. by a polynomial of degree K_r:

$$r(n) = \left\{ r_i ; r_i = \sum_{k=0}^{K_r} b_{r,k} \frac{n_i^k}{\hat{b}_{r,k}} ; i = 1,2,...,N \right\} \qquad (3)$$

where the polynomial parameters $b_r = \{b_{r,k};\ k = 0,1,...,K_r\}$ are normalized as in Eq. (2). An example of the course of polynomials $x(n)$ and $y(n)$ is shown in Fig. 1.

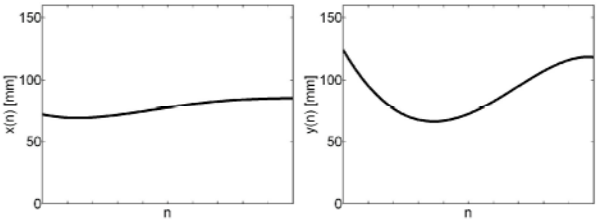

Fig. 1. Course of the curve coordinates $x(n)$ (left) and $y(n)$ (right) in the curve sample space.

2.2 Optimization procedure

In each step of the multidimensional optimization procedure we estimate the cost function for the proposed set of polynomial parameters. Each curve sample n_i; $i = 1,2,...,N$ is mapped to the 3D image space coordinates $c_i = (x_i,\ y_i,\ z_i)$ (Eq. (1)) and to the radius r_i (Eq. (3)) of the surrounding tubular structure over the union of parameters $b = b_x \cup b_y \cup b_z \cup b_r$. A normal plane S_i to the curve is then extracted at each sample n_i from the distance map D, and the sum of all distance map values within radius r_i is calculated. The optimization procedure searches for the set of parameters b^{opt} that maximizes the sum of distance map values in all normal planes:

$$b^{opt} = \arg\max_b \sum_{i=1}^{N} \left(\sum_{r_i} \left(S_i(n_i, b) \subset D \right) \right) \qquad (4)$$

As we set the distance map values to be negative outside the bone structures, we expect that the sum in Eq. (4) will increase until the critical radius (i.e. the boundary of the vertebral bodies) is reached. We initiate the optimization procedure with polynomials of a specified degree. When the termination criterion of the optimization is reached, the degree of the polynomials is increased and the procedure is restarted at the next level, using the resulting polynomial parameters as the new initial values (Fig. 2). The procedure is repeated iteratively and finally stopped when the polynomial parameters at the highest degree are equal to zero.

2.3 Describing natural rotations of vertebrae

The obtained spine curve determines the first coordinate of the new coordinate system. In order to cover the description in the 3D space, two additional coordinates must be determined. One of the coordinates will describe the directions of the natural rotation of the vertebrae around the spine curve. This direction can be determined by finding the axis of symmetry in each cross-section of the spine in a 3D image and the corresponding plane normal to the spine curve (Fig. 3).

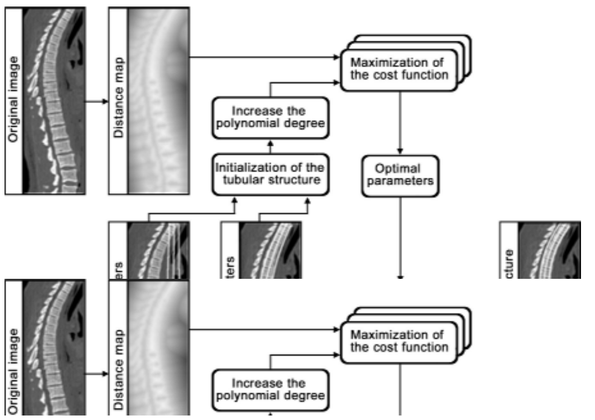

Fig. 2. Optimization procedure for extracting the tubular structure that follows the curvature of the spine.

From the original image I, a normal plane to the curve is extracted at each sample n_i. On this plane, the circle with radius $r_i = r(n_i)$ represents the boundary of the tubular structure at the current curve sample. If we sample the circumference with $2L$ samples ($\Delta\varphi = \pi / L$), then we can generate for each sample n_i; $i = 1,2,...,N$ a set of samples f_i, obtained by summing the image intensities on the line that stretches from the center of the circle to the chosen sample on the circumference:

$$f_i = \left\{ \begin{matrix} f_j ; f_j = \sum_{r=0}^{r(n_i)} \left(S_I(n_i, b^{opt}) \middle| (r, j\Delta\varphi) \subset I \right); \\ j = 0,1,...,(2L-1) \end{matrix} \right\} \quad (5)$$

From this set of samples, we form two non-overlapping subsets, each containing L samples (i.e. samples that belong to circumference inside the π angle):

$$f_i^+(\varphi_i) = \left\{ \begin{matrix} f_i(\varphi_i), f_i(\varphi_i + \Delta\varphi), ..., \\ f_i(\varphi_i + (L-1)\Delta\varphi) \end{matrix} \right\}$$
$$f_i^-(\varphi_i) = \left\{ \begin{matrix} f_i(\varphi_i - \Delta\varphi), f_i(\varphi_i - 2\Delta\varphi), ..., \\ f_i(0), f_i(2\pi - \Delta\varphi), f_i(2\pi - 2\Delta\varphi), ..., \\ f_i(\varphi_i + L\Delta\varphi) \end{matrix} \right\} \quad (6)$$

where φ_i denotes a chosen starting angle. The correlation $R_i = R_i(\varphi)$ coefficient of these two subsets is equal to:

$$R_i = \frac{\sum_{j=1}^{L} \left(f_{i,j}^+ - \bar{f}_i^+ \right)\left(f_{i,j}^- - \bar{f}_i^- \right)}{\sqrt{\sum_{j=1}^{L} \left(f_{i,j}^+ - \bar{f}_i^+ \right)^2 \sum_{j=1}^{L} \left(f_{i,j}^- - \bar{f}_i^- \right)^2}}; i = 1,2,...,N \quad (7)$$

where $\bar{f}_i^+$ and $\bar{f}_i^-$ denote the average values of the subsets $f_i^+(\varphi_i)$ and $f_i^-(\varphi_i)$, respectively. We then search for the angle φ_i^{opt} (the circumference sample) with the maximum correlation coefficient:

$$\varphi_i^{opt} = \arg\max_{\varphi} R_i(\varphi) \quad (8)$$

As it can be seen from Eq. (6), the subsets f_i^+ and f_i^- are equal over π, thus the angle search space can be limited to the range $-\pi < \varphi < 0$. The correlation coefficient $R_i(\varphi)$ can be interpreted as a measure of similarity between the two halves of the extracted circular plane obtained by intersecting the plane through its center.

To increase the robustness of the procedure, the samples f_i can be calculated as an average over a specified number of planes before and after the current plane. The resulted angle φ_i^{opt} determines the axis of intensity symmetry that is oriented in the direction of the vertebral spinous process, therefore it describes the natural rotations of the vertebra around the spine curve (Fig. 3) and represents the second coordinate of the new, spine-based, coordinate system (the spine curve determines the first coordinate). Orthogonally to this direction we define the third coordinate, which therefore extends in the direction of the vertebral transverse process. The coordinates, obtained by finding the axis of intensity symmetry on an arbitrary normal plane to the curve, are defined for the current curve sample n_i and therefore their direction varies when moving along the curve. For the whole sample space, they can be uniformly determined by a set of angles $\varphi^{opt} = \{\varphi_i^{opt}; i = 1,2,...,N\}$.

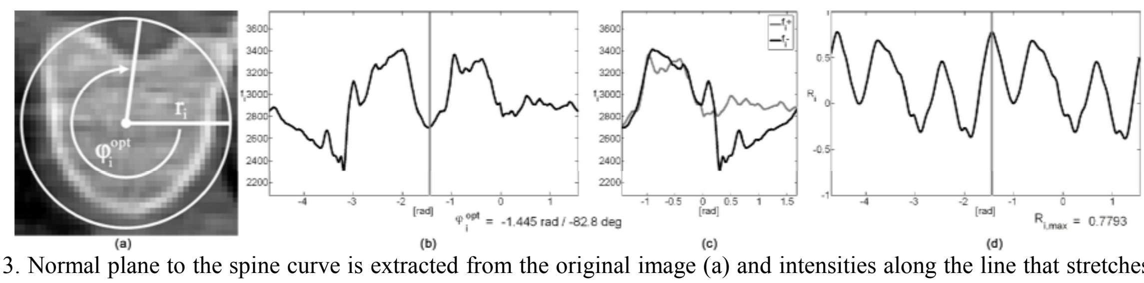

Fig. 3. Normal plane to the spine curve is extracted from the original image (a) and intensities along the line that stretches from the center to the boundary of the tubular structure are summed at each circumference sample (b - Eq. (5)). The similarity of the two halves of the obtained values (c - Eq. (6)) is determined by calculating the correlation coefficient at each circumference sample (d - Eq. (7)).

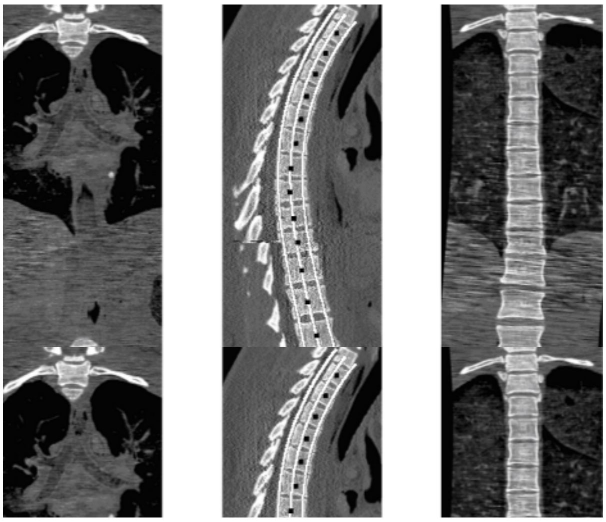

Fig. 4. Effect of applying CPR to CT spine data. In standard reformation, the whole course of the spine segment can not be seen in a single planar image (a). Generation of an image that follows the curved path of the structure (b) allows viewing the image in the coordinate system of the spine (c). Note: The shown curve and landmarks are a projection to 2D view.

3 Experiments and results

The presented method was tested on a single CT spine segment that corresponds to Visible Human (VH) data (image size: 573×330×774 voxel; voxel size: 1.0×1.0×1.0 mm/voxel; number of vertebrae: 18). User interaction was limited to the selection of the upper-most and lower-most vertebral bodies that determine the section of the spinal column that is to be described by the curve. The number of samples (N = 500) was set to the approximate value of the number of voxels between the selected points in the z-direction. The initialization of the curve was equal to a straight line between the selected points. We wanted the curve samples to be equidistant in z-direction, thus we fixed the degree of the polynomial $z(n)$ (Eq. (1)) to the initial value ($K_z = 1$), forcing the course of the z-coordinate to be always linear.

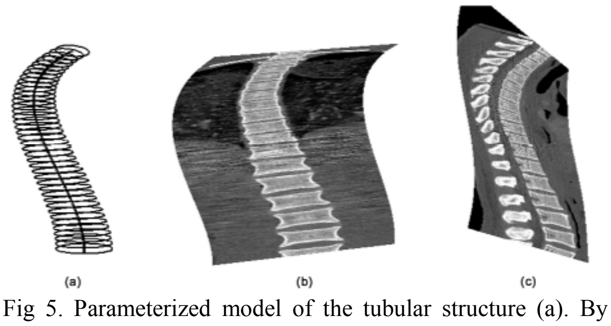

Fig 5. Parameterized model of the tubular structure (a). By moving along the centerline, curved planes can be extracted (b - sagittal view, c - coronal view).

The optimization procedure was implemented using the downhill simplex method in multidimensions. The resulting spine curve in the parametric form of a 4th degree polynomial well described the curvature of the spine segment (Fig. 4). Different images could then be generated using the obtained CPR results (Fig. 5).

The landmarks that represent the centers of vertebral bodies were used to assess the performance of the centerline extraction algorithm. The centerline extraction error was measured quantitatively as the Euclidian distance from the landmarks to the curve that represented the curvature of the spine (Table 1).

Distance	Value [mm]
Maximal distance	4.97
Minimal distance	1.27
Mean distance	3.32

Table 1. Centerline extraction error.

4 Conclusions

We present an approach to curved planar reformation of CT spine data. The proposed method is completely 3D oriented and thus allows to measure actual 3D features of the spinal column rather than depending on 2D features. Transforming a CT spine image from the image-based to spine-based coordinate system reduces the structural complexity of the spine, which is due to the natural curvature of the spine and the natural rotations of the vertebrae around the spine curve. Furthermore, the proposed parametrical model of the spinal curvature can be deformed to fit both the natural and pathological curvatures of the spine, which could be useful for objective evaluation of pathology of the spine (i.e. scoliosis). The CPR technique does, however, have some limitations. Distances should not be measured from CPR images as they are referenced to the spine-based instead to the image-based coordinate system. On the other hand, if the structures are identified in CPR images, their positions can be mapped to the standard reformation where distances can be measured.

In general, the presented method facilitates image manipulation and computer-assisted applications (e.g. removing the spine before extracting maximum intensity projections of [6]). Different approaches to spine segmentation usually make use of a model of the spinal curvature that takes into account spatial relationships between vertebrae. If a way is found to estimate the location of each vertebra on the extracted curve, the models would gain on accuracy and be more effective in assisting high level techniques (e.g. segmentation). Different classes of spinal deformities have to be considered, and consequently different model templates have to be produced. An example for spine segmentation is the utilization of a statistical shape model for a single vertebra, such as the one for the lumbar vertebra that we presented in our previous work [16, 17]. Vertebrae in the spinal column could be allocated by traveling with the model along the spinal curve. The course vertebral rotation can be exploited not only to determine the rotation of a vertebra relative to neighboring vertebrae (i.e. inter-segmental rotation), but also to determine the rotation present within individual vertebra between its superior and inferior end plates (i.e. intra-segmental rotation), which are important especially in cases of scoliotic spines. If such techniques can be successfully applied for assessment of spinal curvature and rotations of vertebrae in an individual subject, surgical interventions and clinical therapy planning may be improved.

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Tomaž Vrtovec received his B.Sc. degree in electrical engineering from the University of Ljubljana in 2002. He is currently employed with the Laboratory of Imaging Technologies at the University of Ljubljana, Faculty of Electrical Engineering, Slovenia.