Quality and Speed Improvements in Industrial CT by the Use of an additional Optical Sensor

Matthias FRANZ, Dr. Stefan KASPERL, Fraunhofer Entwicklungszentrum Röntgentechnik EZRT, Fürth, Germany

Abstract: A method for quality and speed improvements is introduced for a CT with exactly known model. The intention is the exploitation of the knowledge of the model for the correction process. We show that at least with an additional optical sensor we are able to register the model by a few projections only and during the data collection. Until now non-linearities in the CT as beam hardening were corrected by a process that needs a binary volume gained by a time-consuming post processing. With the known model pose we are able to perform the correction for the non-linearities already during the data collection. This means a great gain of time. Also the length derived the models will be more accurate than the lengths gained by first binary volume that still might possess some artefacts.

1. Introduction

When testing 3D-items it is very difficult to gain information on the whole object. If optical sensors are used, there is e.g. only information on the (visible) surface available. The industrial CT is a testing device, that provides information on the whole 3D-item. It is able to provide a (discrete) function that represents the extent of attenuation of the X-rays. The problem is that without a correction such functions show artefacts, i.e. they will not display the real attenuation quite well. This is due to the fact that the consequences of interaction between the X-ray and matter do not correspond to the assumptions of the mathematical theory of CT.

If nowadays the requirements on the accuracy of the CT become stricter, the need of an effective correction becomes more important. Such a correction technique is the I(terative) A(rtefact) R(reduction) which has shown good results [2]. The main inputs of this method are the propagation lengths of the X-rays in the matter. But to get these lengths there have to be done some quite time-consuming iterative post processing steps. And this can be a great burden, especially if you operate on detectors with high resolution, i.e. > 2048 x 2048.

One application that requires an especial accuracy is the use of the CT as a measurement device for production control. For example in case of an item with a dimension of 10 cm, an effective correction is required in order to achieve an accuracy of less than 0.01 mm. Now the difference to a normal CT is the additional knowledge of the item that is scanned. The idea is now to use data gained from the model to support the correction process. To do this, the model has to be registered, i.e. the poses during the CT scan have to be identified. With the known pose you can start a Virtual CT, i.e. a simulated CT that can be used to provide the length needed by the correction without any post processing steps.

This paper is arranged as follows: In the 2nd section the IAR correction method is explained. In the 3rd section our registration procedure is explained. In the 4th section we give the first results, and in the last section we discuss the results and give some future prospects.

2. IAR

The key for the CT is the fact that X-rays are attenuated by matter. If you have mono-energetic X-rays they will be attenuated according to Beer's law [4]. In this case the attenuation behaves linearily. So if you plot all data points consisting of the length and the attenuation values this will show a linear relationship. But there are mainly two effects that cause it not to be linear. These are beam hardening and scattering. And this yields to artefacts in the reconstructions as the whole CT process assumes a linear relationship.

The IAR transforms the measured intensity values, which appear to result by a highly non-linear process into values, that show a linear behaviour again [1][2]. The idea of the correction is to identify the relationship between the lengths and the attenuation. This relationship can be caught by a fitted function. Now you can identify the mapping that transforms this non-linear relationship into a linear one and apply it to all measured values. So the transformed intensity values appear to be linear and the normal reconstruction can be applied. The key input to identify the non-linear relationship in the originally measured attenuation is the knowledge about the propagation lengths of the X-rays in the matter. And these lengths are extracted out of a binary volume of the item that is provided by a time-consuming post processing step. And often, if the first reconstruction has too strong artefacts the number of necessary iterations in the IAR is quite large.

3. Registration

The registration process can roughly be described as the search for the transformation that maximizes the similarity between a reference image *R* and the transformed template image *T*. The similarity function is actually the heart of every registration as it is a crucial point for a successful registration. The specific in 3D/2D-registration is the point that you only have 2D-mappings of a 3D-item to evaluate the similarity. There are two completely different concepts. The feature based approach extracts some features (e.g. line, corner ...) from the projections and the registration tries to find correlations. And the best mapping between the corresponding features represents the sought transformation. The other approach is called intensity-based. Here preprocessing steps are omitted, the whole set of pixel values is taken to evaluate the similarity. This is the approach for the registration that is done in this paper. Now the job is to register a 3D-CAD model with a few intensity projections at most. The registration process can be divided into two main parts. First a coarse registration has to be done. Often this is a manual process [3][6]. But in this paper the aim is to do this step automatically as the registration process should be done without human interaction. When the coarse registration was successful a good initial value for the optimization should be found and the fine registration now can be done in a step-by-step optimization procedure [3][5].

To measure the similarity we will use Mutual Information. Its great advantage is the ability to handle multimodal data due to its statistical character. This fact becomes even more important if you think about the connection of the multimodal data we will use. As there will approximately be just a multiplicative factor between them the statistic of the data will remain the same. So Mutual Information will act as if we would have unimodal data. This fact makes this measure more advisable.

3.1. Initialization

Before starting the registration process has to be initialized. Most of it is done by passing a Virtual CT to the registration module as it contains all important parameters of the CT.

Among others these are distances between the assumed point source and the rotary disc and between the rotary disc and the detector. Also some parameters of the detector like the size and the pixel resolution are important. But now a crucial point is how the references that are constituted by the projections are passed. The projections are assumed to carry the full shadow of the items that are scanned. If the registration obtains the raw projections it has two options. Either it can perform the registration by a complete simulation of the template projections or it can register in a multimodal way, i.e. by comparing the raw projection with a partly simulated projection, say only the lengths. The first way will consume more time than necessary and the second complicates the evaluation of the similarity. A way to evade this problem is to pass some other kind of projection. The key of the Virtual CT is a very fast implementation. The calculations are done on the graphical processing unit. So a fast registration should be able to handle length projections. So a good reference image would be one that presents the monochromatic attenuations. They would constitute a proper reference as the monochromatic attenuations are multiples of the lengths. And Mutual Information (MI), which is the similarity measure that will be used, doesn't care about multiplicative factors.

The conversion of the polychromatic attenuations into monochromatic will be done by a converter that is described in the following section.

3.2. The PM-Converter

Of course the evaluated attenuations depict the values of polychromatic attenuations. So we use a module which converts the real attenuations, which are polychromatic, into monochromatic attenuations (therefore PM). The key of this converter is a simulation for polychromatic attenuation, i.e. for a given spectrum and material we simulate the polychromatic attenuation as a function of the lengths. For every measured attenuation the inverse of this function will give the associated length and therefore by a linear relationship

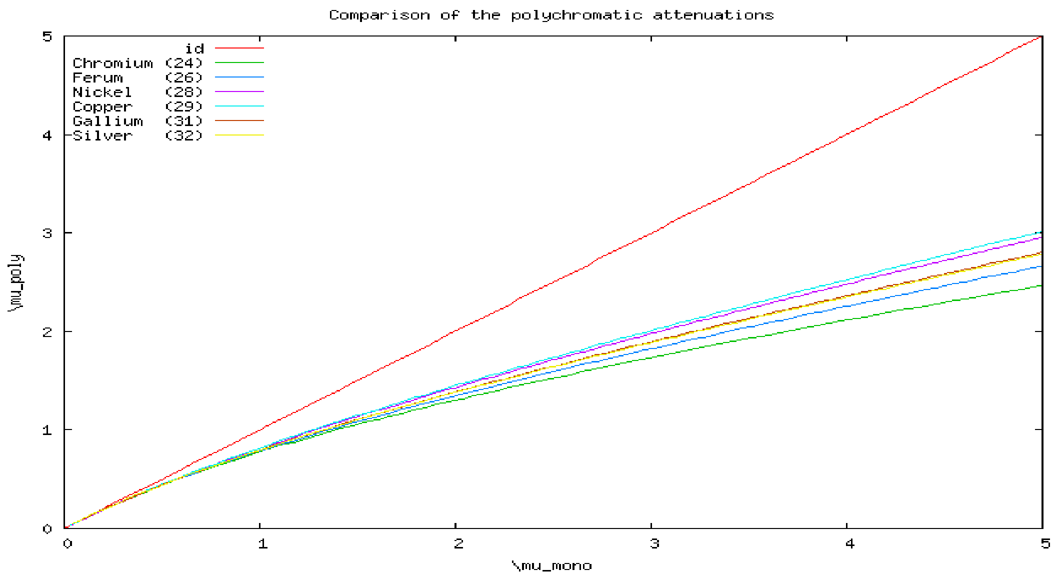

Fig. 1: Comparison of the monochromatic with the polychromatic attenuation.

the monochromatic attenuation. One may criticize that this implies knowledge of the material and of the adopted spectrum. This is right, but as the IAR is only practical for homogeneous items, a rough knowledge about the material can be assumed. And Fig. 1 implies that this is sufficient.

As the calculations for such a PM-Converter last at most 2 sec. the converter is no extra burden and therefore should always be employed.

3.3. Coarse Registration

The problem of a correct registration can be seen as kind of optimization. You look for the pose, i.e. the translation and rotation, for which a reference and a transformed template image show the greatest similarity. Now the problem is that in 2D/2D- and 3D/3D-registration the similarity function will have several local extreme values. And the problem becomes even bigger if you have to perform a 3D/2D-registration. Without any details you can imagine this fact as the number of free parameters grows (4 -> 6). But even in the cases with the same dimensionalities this local extremal values stand for big problems that make it advisable to start for fine registrations not too far away from the optimal value.

The rigid transformation has 6 degrees of freedom, i.e. 3 for the translation and 3 for the rotation. This registration procedure assumes no other constraints on the item than its shadow fitting on the detector. This implies that no natural landmarks can be postulated that could facilitate a coarse registration [7]. It follows that you have to start with an empirical search. Due to the 6 degrees of freedom a search for all transformation parameters will exceed every reasonable effort. If you choose only 15 sampling points per parameter you will have to evaluate the similarity for over 11 million transformations. So there must be another way which figures out at least some of the free parameters.

The transformation of a real item can be described by the transformation of its barycentre. Once the item has to be translated, the rotation *R* has to be performed around the barycentre so that this point remains fix. If now the translation of the barycenter is known, only 3 additional parameters have to be sought. With *G* the domain of the item the 3-dimensional barycenter $\bar{x}$ can be evaluated by

$$\bar{x} = \int_G w(x) x dx$$

with *w* a proper weighting function, that equals 1 for homogeneous objects. As the aperture angle normally is below 10° we now approximate the fan beam by the parallel case. The crucial consequence of this approach is the identity of the barycenter of the projection and the projection of the barycentre of the item. This implies a barycentral line, i.e. a line from the source to the barycenter of the projection that contains the barycenter of the item. Now we have at least two projections. The barycenter of the item now is the intersection of two barycentral lines. As an approximation was used, don’t choose the intersection but the point that has the minimal distance to all barycentral lines.

The second part of the coarse registration is the determination of the rotation. If the rotation is expressed by the three Euler angles this means three remaining free parameters. This dimensionality poses a practicable job for doing it empirically by testing the similarity on a proper grid. The question is now how to find a proper grid? While using the presentation with Euler angles this will be a difficult task. Therefore it seems to be advisable to choose another presentation of the rotation. We use the mathematical fact that every rotation can be seen as a single rotation around an arbitrary axis, which then is a unit quaternion. As no axis stands out this fact makes it easy to create a uniform distribution of rotations [8]. You have to choose an evenly distributed set of vectors on the sphere and for every vector perform the rotations by an angle in $[0, \pi]$. Anyway there will remain a great number of poses for evaluating the similarity. To handle this number the resolution of the detector is reduced to 64 x 64. For this resolution the time for rendering the approx. 3000 length projections and evaluation of their Mutual Information was approximately 1 min. The results of this evaluation are put to a stack.

Now we apply the optical sensor. We used an optical sensor called *Kolibri* developed by the Fraunhofer IOF that provides coordinates of the visible surface. These coordinates are used for testing the stack as now most of the stack poses can be discarded due to its deviation with the coordinates of the optical sensors.

3.4. The fine registration

The fine registration is effected according to a scheme that is called multi-resolution approach [5]. I.e. for optimization you refine the resolution step by step. First the pose is optimized for a 64 x 64 projection. The next optimization step uses a 128 x 128 resolution, and so on until in the last step the pose is optimized for the full resolution. The advantage of this procedure is a time gain. As in the case, where the optimization steps are not too small, a coarse resolution will also indicate the right similarity behaviour. But the time for generating the length projections is linear with the number of pixels, so the generation of a 1024 x 1024 projection will last 64 times longer than a 128 x 128 projection.

The optimization was split into an optimization of the rotation and translation. For both we applied a downhill simplex method in multi-dimensions [9]. In our experiments this optimization strategy showed the best result, but other authors used other strategies as e.g. Powells multi-dimensional direction set method [10].

As mentioned the coarse registration provided a stack of initial poses. These were ordered in a descending order, i.e. the coarse registration with the highest similarity value was at the top. If now the whole stack of initial poses has to be processed with a fine registration this will last too long. So we had to make a rule when to stop. For this purpose we used the Normalized Mutual Information (NMI) rather than MI. With *H* the entropy *NMI* is

$$NMI(X,Y) = \frac{H(X)+H(Y)}{H(X,Y)} \ ,$$

see [11]. The advantage of this measure is its codomain that is [0, 2], where 2 stands for two perfectly aligned images. So the absolute value of this measure is a level of the similarity. This enables us to stop the processing of the stack if the *NMI*-value exceeds a certain value.

4. Results

For testing the method two test phantoms (AcTech1a and AcTech3b, see Fig. 2) were constructed and CT scans were performed. For both items also the STL-data were available. The projections of AcTech1a had a resolution of 1024 x 1024 whereas these of AcTech3b only of 512 x 512. For registration purpose of AcTech1a we used the projections 0, 114 and 228 of the overall number 800 which means an angular interval of slightly over 100°. In the case of the AcTech3b we used the 1st, the 75th and the 150th projection of 400 which means an angular interval of 135°. The size of the angular interval is mostly needed to approximate the translation of the barycenter. This becomes clear if you imagine that there is no depth information contained in a single projection. The depth information opens up by several views which should possess a significant angular increment. But an increment of little more than 100° seems enough. If the last projection of the used projection is done, the actual approximation of the barycenter lasts only 1-2 sec.

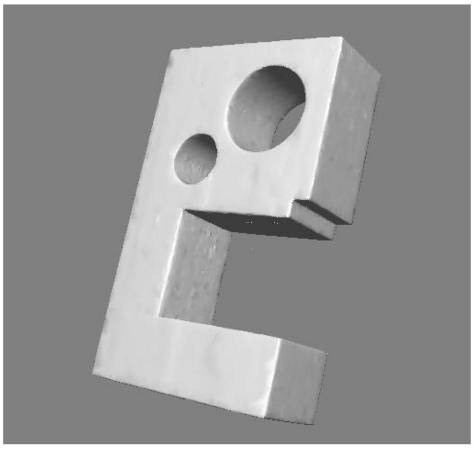

Fig 2a) AcTech1a

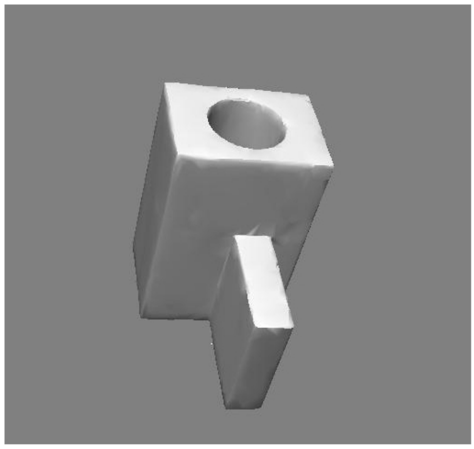

Fig. 2b) AcTech3b

The greatest part of the coarse registration remains in the determination of the rotation. This was done by the evaluation of the information at a sufficiently fine grid. The time used for this task is nearly independent of the original resolution of the input projection. This is because we reduce the resolution to 64 x 64 anyway. As we wanted to avoid the burden of

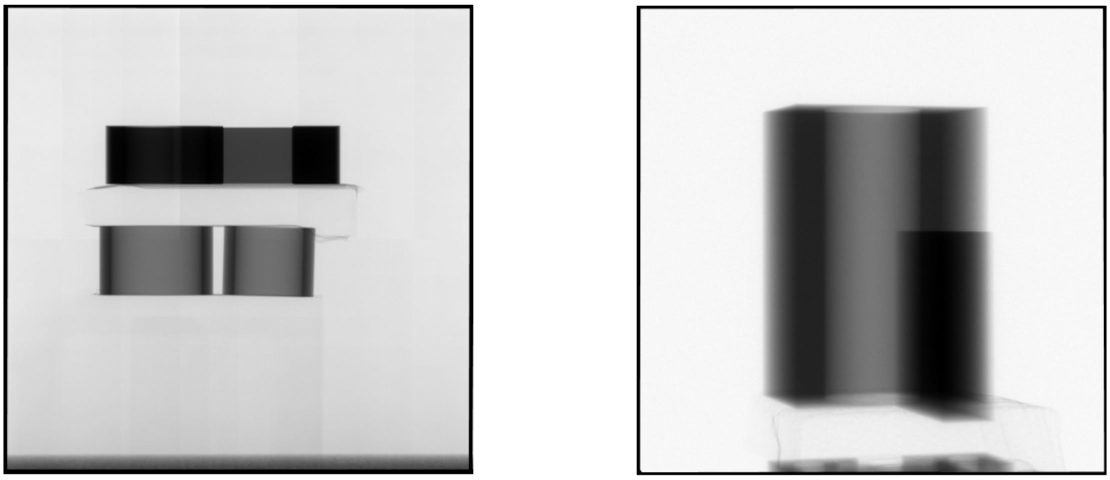

Fig 3) Projections of AcTech1a (l) and AcTech3b (r). On the left side you see also two items for calibration.

handling the 64 x 64 projection in the fine and in the coarse registration, we partly merged both steps. I.e. we immediately performed the fine registration for the 64 x 64 projection during the coarse registration if the Mutual Information was high enough on the grid point already. All together the coarse and some of the fine registration part last 45-60 sec. The last part of the registration was the fine tuning of the pose. For this part we used techniques from the medical image registration as in [5][6][11]. As you will see later the IAR needs no perfectly aligned item. A registration with an error of rotation in the magnitude less than 0.2° and an error of translation less than 0.1 mm will do.

Fig. 4 shows the comparison of the intensity/length-data that were generated from the binary volume and the proposed method respectively. The lengths are drawn on the *y*-axis, the intensities on the *x*-axis. The quality of the data pairs becomes even slightly better. The main improvement can be seen in the regions with big intensities, i.e. bigger than 25000 gray values, and small lengths, i.e. smaller than 10000 μm.

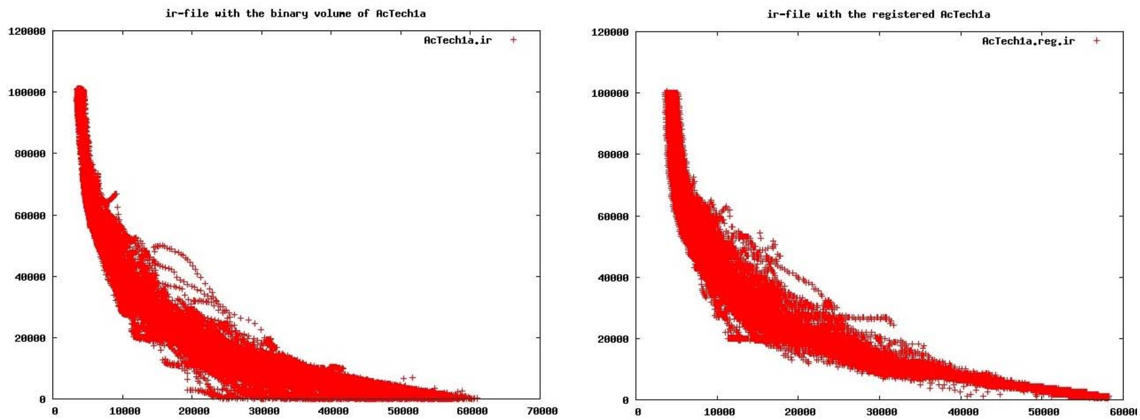

Fig. 4) The image on the left depicts the ir-data for the AcTech1a that are generated by the traditional method. On the right side the data pairs are generated with the proposed method.

The next comparison was made for the item AcTech3b. Here too the differences weren’t very significant, there are only small improvements. As for the correction the crucial inputs aren’t the data pairs but the functions that are fitted through the data pairs, those are shown next. Here you see that the differences are very small or even not noticeable. So the results of the correction won’t change whatever method you will choose.

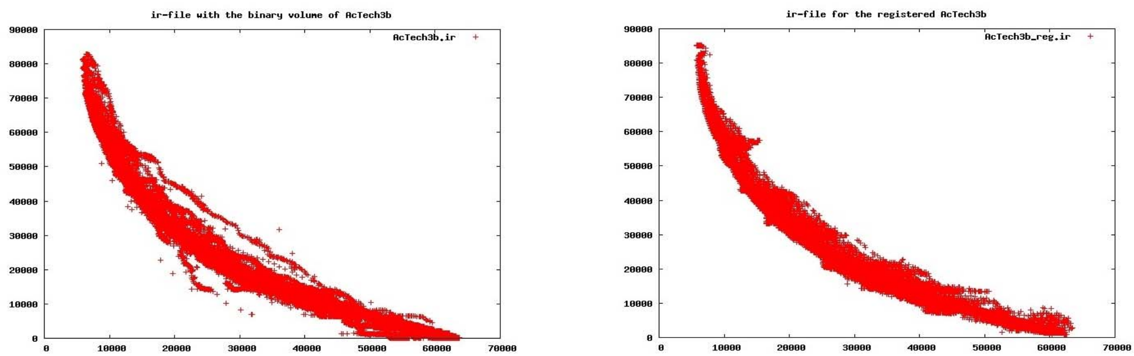

Fig 5) Comparison of the ir-file generated with the binary volume (left) and the ir-file generated with the STL-data of the AcTech3b

5. Conclusions

Our aim was to obtain the lengths of the X-rays in matter by a registered STL-volume instead of using the binary volume which means a time-consuming post processing step. We have shown that with the input of the STL-volume, the geometry and 2-3 projections out of an angular range of about 100 degrees we were able to register the STL-model. The registration lasts for about 2-3 min. This means the registration is finished before the CT data requisition. As the time for the fitting routine is unessential we will be able to correct the measured data online without any time delay but have the same results as you see in Fig. 6. At this stage the fast registration is limited to items whose shadows are completely on the detector. The next steps will be the expansion of this method of corrections for items that are too large to completely fit on the detector.

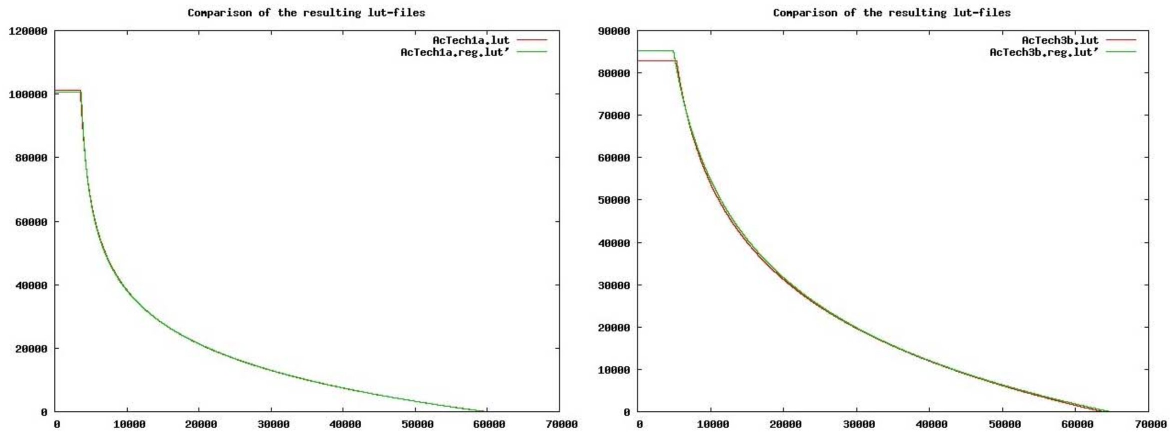

Fig. 6) Comparison of the correction functions that were generated with the traditional and the proposed method resp. (left: AcTech1a, right: AcTech3b)

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