Automation of a CT Acquisition: A System-based User-Support

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Abstract

TheComputed Tomography (CT) is one main imaging technique in the field of non-destructive testing. Depending on the parameter configuration for a CT scan, a high-quality volume of an object can be achieved. Since the dependency between an adequate definition of the parameters and the resulting volume quality is very strong, a scan requires certain amount of CT knowledge for parameter optimization. In this paper, an approach of a system-based user-support will be regarded. Possible automatic parameter optimization steps will be presented and discussed. Since CT spreads into industry, more users are beginners; but also for experts these initial parameter settings, estimated by the system, are a valuable support for the final CT acquisition as well as a starting point for the manual parameter definition. This automatism will lead to less workload for the operator and to a good balance between the individual CT knowledge of the user and the system measured information.

Keywords: Image processing, computed tomography (CT), acquisition parameters, automatic acquisition, user-support

1. Introduction

In the past ten years computed tomography (CT) has become more and more popular in the industry. Pushed by the general trend of saving resources most new developed parts have been designed with more complex inner structures or higher demands in accuracy due to reduced material. These trends lead to an even higher need for testing, especially of inner structures. In the last decade CT-based imaging has been established as one of the most versatile technologies in sophisticated laboratories all over the world. Starting from research facilities spreading into the central labs of global companies, CT has now arrived in the production facilities and none destructive testing (NDT) departments in the industry. This development leads to a change of the typical user profile. In the early years of industrial CT the typical user was a scientist or highly educated engineer, who had not only an in-depth understanding of the physics and mathematics of computed tomography, but was also willing and able to adjust every detail in the settings of the CT system. Regarding the production the operator has neither the time nor inclination to develop a deep understanding of CT technology. CT systems designed for operators in a production environment need to have a much higher grade of automation, enabling the user concentrating on his main task, the none destructive testing without being bothered by system settings.

Computed tomography has a much higher level of complexity compared to digital radiography (DR). Furthermore, it takes minutes or even hours before the results and thereby the quality of the settings can be reviewed in the CT data. Without tough time constrains many user are scanning an object more than once in order to optimize the settings of the CT system iteratively.
Even simple tasks, as defining the right magnification and by that the size of the inspection envelope (see section 2.1), are much more complex than with DR. It might be easy to see in the first projection, if the object fits into active area of the detector, but for CT this requirement has to be fulfilled for all projection angles of the whole acquisition. This often leads to lengthy procedure of moving the magnification axis and rotating the object.

The next important step is setting the parameters of the X-ray tube and the detector (see section 2.4). This is a not too difficult task for conventional closed fixed focus X-ray tube when using DR. Regions with a lack of penetration or with a saturated detector can be easily seen in the live image. The high-voltage and tube current or detector mode can then be adjusted accordingly [1]. Depending on the detector type it is not unusual to use different settings for different areas of the object. However, the settings of the X-ray tube are much more critical for CT scans. Not only it is necessary to use a single setting which results in adequate projection values for all regions of the X-ray projections, but also a lack of penetration or saturation of the detector have adverse effects for the results of the reconstruction algorithms (see Figure 5). If higher resolutions are needed so-called microfocus X-ray tubes are used. These kinds of X-ray tubes are equipped with an electron optical system in order to achieve smaller focal spots. This introduces an even higher degree of complexity by extending the parameters by two dimensions: The focal spot size itself and the mode of the electron optics.

Therefore, CT systems designed for the use closer to a production environment should offer automated procedures setting these basic parameters, enabling the user to concentrate on his main task - the inspection of CT results.

In the following section 2 we will introduce our approach of a system-based user-support. In section 3 we will give a short overview about the different user modi and Section 4 will conclude with a short discussion of the current state of automating CT acquisition.

2. CT Parameter: Dependencies and Automatic Optimization

In the following a user-support strategy for a CT acquisition is presented. Different parameters are regarded which need to be defined adequately, to gain a good quality of the resulting CT volume. For these parameters automatic adjustment processes are proposed.

2.1 Object Size

A CT acquisition without any prior information is searched. Hence, the object size has to be determined in a first step. Without this information, no further motion, e.g. of the object itself, the X-ray tube or the detector, is possible without leading to collisions between the different components.

To gain the needed object information, volume recognition is proposed which results in an approximation of the outer object boundaries. A virtual, digital model of the object can be generated which has to be connected with the world coordinate system of the object manipulator. Based on such a model, the maximal object size can then be extracted. One possibility, to define these maximal boundaries is a set of parameter pairs \((h, r)\), where \(h\) represents the position in vertical direction along the rotation axis of the turn table with the object and \(r\) gives the maximal radius of the object for the current vertical position \(h\).

Figure 1 shows an example of such a three-dimensional object model. Here, two of the three needed maximal object sizes are illustrated by the red arrows. Using these sizes for comparison with the system model leads to a set of allowed motions without any risk.
Furthermore, a set of motion which would lead to a collision can be extracted and therefore excluded for further modifications of the system.

![Image](image.png)

**Figure 1 Example of a three-dimensional object model. Based on this model, the maximal object size for each dimension can be extracted. These values are needed to avoid any collisions during further motion of the object or other components of the system.**

Many different methods for such a needed surface extraction have been proposed in the past. For example stereoscopic or multi view approaches are described in [4] and [5] in detail.

### 2.2 Object Position

The position of the object in relation to other components of the system should be changed only with the information about the object size to avoid any collision. After the identification of the object size, as described in section 2.1, the object can be positioned in an optimal way. Parameters, which are involved in this process, are:

- the distance between the focal spot and the detector (FDD)
- the distance between the focal spot and the object (FOD) and
- the vertical position of the object (o_v).

Again, it is expected that no prior information is given to the system. Hence, the optimal position is defined in the following as the position where the object optimally fills the projection image.

With the known object size the optimal magnification

\[ M = \frac{\text{FDD}}{\text{FOD}} \]  

(1)

can be defined, where the object fits into the projection on the detector in vertical as well as horizontal direction for all projection angles. Objects, which are clearly larger in one dimension, have to be cut at the projection image, if such an optimal position is not found.

To define M a restriction of the minimal FDD may be used as another condition. It is known that the angle of the X-ray beam \( \alpha \) should be smaller than 10° to reduce the amount of so-called FDK artifacts inside the reconstructed volume (see [2]). Using this restriction, the FDD can be defined as followed
\[ \tan\left(\frac{\alpha}{2}\right) = \frac{D_h}{2 \cdot \text{FDD}} \iff \alpha = 2 \cdot \tan^{-1}\left(\frac{D_h}{2 \cdot \text{FDD}}\right) \Rightarrow \text{FDD} > \frac{D_h}{2 \cdot \tan(5^\circ)}. \quad (2) \]

The parameter \( D_h \) represents the horizontal physical size of the detector, which is known. With the further restriction, that the FDD should be as small as possible to reduce the X-ray length and to increase the signal at the detector, the FDD can be defined as the smallest size which holds the above mentioned inequality. With the fixed FDD the FOD can then be defined by fitting the object projection on the detector. Finally, with a fixed magnification \( M \) the position \( o_v \) can be optimized by fitting the object projection in vertical direction on the detector as well.

Figure 2 (a) shows an exemplary projection image of an object which is positioned not optimal concerning the above mentioned definition. By minimizing the background areas around the image in each projection image, an optimal position of the object can be found (see Figure 2 (b)).

![Figure 2](example_image.png)

**Figure 2** Example for an optimal object positioning: (a) the initial position of the object is not optimal, since the projection of the object does not fill the projection image (red arrows) and not all parts of the objects are visible (blue arrow). (b) After optimizing the magnification \( M \) as well as the vertical object position \( o_v \), an optimal projection of the object on the detector is reached (for all projection angles).

Advanced system-based parameter definitions could include an object tilt as well. This modification of the object position can lead to a reduced amount of so-called FDK artifacts inside of the reconstructed volume (a detailed description is given in [2]). The decision, whether such a tilt is necessary for the current image, can be done based on an evaluation of the main object edges on the projection image. If their main orientation is close to the horizontal detector axis, a tilt should be done to avoid strong FDK artifacts.

An example for this kind of artifacts is shown in Figure 3. Depicted are slices of the reconstructed CT volume for the same object with a larger FDD (Figure 3 (a)) as well as a smaller FDD (Figure 3 (b)). Figure 3 (c) shows one of the projection images to visualize the real object structures. The horizontal plate which is marked with a red arrow in all three images shows the growing negative influence of the smaller FDD on the resulting image quality. With the reduced FDD the plate, clearly visible in the projection image, becomes destroyed. With the larger FDD this destruction is obviously smaller.
Figure 3 Example for the influence of the FDD on the resulting cone beam artifacts: (a) projection image of the object, (b) slice of the reconstructed volume of a CT acquisition with a larger FDD and (c) of a CT acquisition with a smaller FDD. The horizontal plate marked with the red arrows is clearly visible in the projection image. With the larger FDD the destruction of this object part is obviously smaller than with the smaller FDD. With the reduced FDD the plate becomes destroyed nearly completely.

2.3 Field of View Extension

Alternatively, a field of view (FoV) extension is possible as well to overcome the cut of larger objects, which was mentioned in the previous section. If the optimization of the object position results in an object cut in horizontal or vertical dimension an FoV extension should be used to involve a larger or if even possible the complete area of the interesting object for a further inspection.

There are several possibilities to realize an FoV extension. The easiest way is moving the detector into the appropriate direction and stitching several X-ray images to one large projection image together. Afterwards, the CT reconstruction is performed usually but for the larger projection images.

A simple way of FoV extension in vertical direction is to stack separate reconstructed volumes of the dedicated vertical levels on top of each other. In practice, this will lead to artifacts at the overlapping regions at the top or bottom of the single volumes respectively. Alternatively, a helix-like trajectory could be used to overcome these artifacts, if the CT system provides this feature. In this case, the CT volume will be reconstructed as one single volume completely and therefore there will be no inhomogeneities at the borders of the single FoVs.

Figure 3 shows an example of an object which is too large for the detector. The object projection moves out of the detector view for certain rotation angles in horizontal direction and for all projection angles in vertical direction. Hence, the FoV extension in both directions should be applied in this case.
2.4 Parameters of the X-Ray Tube and the Detector

The most important parameter for the X-ray tube as well as the detector is the dedicated operation mode. Depending on the components and the manufacturer different modes are possible. For example, three main quality ranges are expected concerning the adequate tube and detector modes:

1. standard
2. full resolution
3. high dose

These modes may be previously defined by the manufacturer. Following the requirement, that no user interaction is needed, an evaluation of first projection images can be used to find the best strategy for the current object starting in standard mode.

As a first evaluation the minimal gray value of each projection regarding the different projection angles will be detected. If the object is not penetrated by X-rays adequately the X-ray parameters have to be adapted or if this is not possible the object has to be rejected and the reason has to be reported to the user.

Assuming that the penetration check above has been passed successfully the projection image will be analyzed using image processing or even feature detection methods (see [5]). One example is the usage of edge detection methods. If the projection image has a large amount of edge it can be interpreted as highly structured. In this case the object is highly structured as well and the full resolution scan mode represents the appropriate choice of strategy.

After answering these questions, the voltage and current of the tube has to be defined. Both parameters have a strong effect on the gray values of the resulting projection image and accordingly on the resulting volume quality.

Two main boundary conditions have to be fulfilled in this context. Firstly, it is not allowed to produce detector saturation because of a too high dose. With saturation object information may be lost as well. Secondly, the object needs to be penetrated adequately. If this is not the
case, the signal at the detector is too low which leads to artifacts inside the reconstructed volume.

Figure 5 shows a projection image of a high attenuating object (a) and the corresponding gray value histogram (b). On the one hand it is obvious that with the used voltage and current the object is not enough penetrated (see the large interval of low values in the histogram). On the other hand the detector is saturated in the background (the histogram shows entries up to the possible maximum of the detector). The ideal case would show a histogram in between the interval [10%, 80%] of the total number of gray values (TNGV) for the current detector. Then, detector saturation can be avoided and all parts of the object are penetrated adequately.

![Image](image.png)

**Figure 5** Example for the main boundary conditions regarding voltage and current of the X-ray tube: (a) Projection image of a highly attenuating object, (b) the corresponding gray value histogram. The X-rays are not able to penetrate the object adequately, which result in a large histogram interval for the lowest gray values. Furthermore, the detector is already saturated at the background, what can be seen in the histogram by the entries at the maximal possible gray values of the detector (here $2^{16}$). The green range corresponds to the interval $[0.1 \cdot \text{TNGV}, 0.8 \cdot \text{TNGV}]$.

As already proposed in [1], the imaging chain can be optimized by an iterative adjustment of the voltage and current, which leads to gray value changes. Increasing the voltage shifts the distribution in the histogram to the right. An increase of the current leads to a stretched gray value distribution. Following [6] and [7] this knowledge can be used as an optimization strategy. Modifying both parameters should approximate the mentioned gray value interval $[0.1 \cdot \text{TNGV}, 0.8 \cdot \text{TNGV}]$.

There is the possibility, that both boundary conditions cannot be hold for the same tube parameters. If the object is highly attenuating, as the example in Figure 5, the lower gray values might stay below $0.1 \cdot \text{TNGV}$ while further increasing of the parameters would lead to a saturation of the detector at other regions. In this case, an optional physically prefiltering is reasonable. However, after this change of the X-ray spectrum, the optimization process has to be repeated.

Figure 6 shows a pair of projection images ((a) and (c)) with the corresponding gray value histograms ((b) and (d)). At the beginning of the optimization for voltage and current the gray value distribution is not in the interval $[0.1 \cdot \text{TNGV}, 0.8 \cdot \text{TNGV}]$ (Figure 6 (a) and (b)). After the iterative change of both tube parameters an optimized distribution has been reached (Figure 6 (c) and (d)). With a stretched gray value histogram more of the available values are used which results in a higher gray value resolution for each projection image of the final CT acquisition.
Figure 6 Example for the optimization of voltage and current: (a) and (c) the projection images as well as (b) and (d) the corresponding gray value histograms. Before the parameter optimization the projection image is too dark (a) and the histogram is not in the recommended gray value interval (b). After the optimization the projection image shows the object adequately (c) and the histogram is in the correct gray value range (d). The green ranges in both histograms correspond to the interval $[0.1 \cdot \text{TGNV}, 0.8 \cdot \text{TGNV}]$.

2.5 Number of Projection Images

There are few definitions in the literature, how to define the number of projections for a CT acquisition automatically. For two dimensional parallel beam CT in [2] the definition

$$N_p = \frac{\pi}{2} \cdot N_d$$  \hspace{1cm} (3)

has been proposed, where $N_d$ is the number of pixels in the detector line. Furthermore, in [3] the definition

$$N_p = \frac{\pi}{4} \cdot \sqrt{N_d}$$  \hspace{1cm} (4)

has been proposed for a three dimensional CT acquisition and the number of pixels $N_d$ for the whole detector array. This method yields an $N_p$ which is an adequate compromise between acquisition time and volume quality. Hence, this method represents a good number of projection images if no user-interaction is given for this parameter.
3. Different User-Modi

As it was shown in the previous part of this paper, the main parameters needed for a CT acquisition can be defined automatically by the system. Different levels of a user-support are possible based on this conclusion:

1. Manual mode: All parameters have to be defined by the user.
2. Semi-automatic mode: All parameters are optimized by the system. The results are displayed for the user as assistance.
3. Fully-automatic mode: All parameters are optimized by the system. The CT acquisition is performed automatically. The user obtains a first volume and can decide in further steps whether this quality is sufficient or an adapted acquisition is needed.

4. Summary and Discussion

The main goal of this work has been an automated setup of CT parameters. As shown above, this is already possible for parameters as setting the right magnification by identifying the outer dimension of the object in an early stage of the data acquisition process and thereby also achieving a collision-free manipulation. Furthermore, a method determining the necessary parameters of the image chain has been presented. With the optimal settings of the X-ray source and detector a high quality of projections can be achieved, leading to good results of the reconstructed data. In the last step the necessary number of projection images has been set.

Today, all these automated parameters have to be set by an expert operator. With methods introduced in this paper the expert gains valuable time in order to concentrate on his main tasks or even tweak the system even further. Therefore, a user level control strategy allows experts to concentrate on task where their knowledge is needed, but also granting them access to all available parameters. In contrast, not less experienced users will be able to operate the system efficiently.

In the future more and more tools will make operating CT systems faster and easier leading to a much broader use of CT in production.

References
