# Evaluation of a Time-of-Flight-based Respiratory Motion Management System

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**Abstract.** In this paper a novel anatomic-like phantom, to simulate human respiratory motion is presented. The phantom is capable to simulate thorax and abdomen motion for surface based respiratory gating systems. This phantom is used to evaluate a system based on time-of-flight (TOF) technology, to detect respiratory motion. It could be shown that the correlation between the reference motion, performed by the phantom and the measured data of the TOF system is 0.65 for a breathing amplitude of 1.5 mm and above 0.80 for amplitudes bigger than 5 mm. Furthermore, the system is capable to detect a breathing frequency of at least 25 respiratory cycles per minute.

## 1 Introduction

In radiotherapy the handling of moving targets is getting more and more important [1]. Moving targets are e.g. tumors which are moving inside the human body due to respiratory motion. These targets can be irradiated efficiently by using respiratory gating. Thereby the tumor is irradiated in a predefined respiratory phase and position. One method for respiratory gating is to acquire an external surrogate respiratory signal. There are several methods to acquire such a signal, e.g., the AZ-733 V by Anzai Medical [2], GateRT by VisionRT [3], the Varian RPM system [4] and a time-of-flight (TOF) sensor-based system [5]. Within this paper an anatomic-like phantom is introduced to evaluate external gating methods by providing reference breathing signals for thorax and abdomen. We are using the phantom to evaluate the TOF-based approach, proposed by Schaller et al. [4] and Müller et al. [6].

## 2 Materials and Methods

In the following we introduce a phantom to simulate human respiratory motion. It can be used to evaluate surface based respiratory gating systems. Such systems have special requirements on phantoms. The shape of the phantom should be human-like and also the motion of the phantom should correspond to human respiratory motion. Existing phantoms for example the Quasar phantom from Modus Medical Devices Inc., do not meet these requirements as they do not provide the correct geometry and motion. These phantoms are also not able to simulate various breathing amplitudes and velocities. Due to the human-like surface, the novel phantom can be used for simulating patient positioning processes as well [7].

We manufactured a plaster cast of a male person and added mechanical support to it's chassis. This mechanical support is used to simulate various human respiratory motion. An 8-bit AVR Atmega32 microcontroller ($\mu$C) with a clock frequency of 16 MHz and 32 kByte flash memory was used. The $\mu$C manages the communication with a PC via USB and controls the movement of the phantom's abdomen and thorax. The abdominal motion is generated by a DC-motor with a rotary encoder as control feedback, the thorax is lifted and lowered with three servomotors (Fig. 1). A plaster cast was used, because the intended use of this phantom is to evaluate surface based systems. The intra-abdominal motion of the organs was simplified as a lift and lowering of the abdominal surface. The rotatory movement of the ribs, according to the spine, resulting in a 2D movement of the thorax, is simulated as a rotatory movement by the servo-motors. Using these components various respiratory motions can be simulated. The corresponding reference signals can be used as ground truth for correlation computations and evaluation.

The reference signal is a cosine-shaped signal which simulates human respiratory motion. The thorax performs a rotational movement, whereas the abdomen a linear up and down motion. The phantom can be parameterized using a software tool. Various frequencies and amplitudes for both, thorax and abdomen can be set. It is also possible to simulate the connection of both respiratory systems using a couple factor. In general, the system is also capable to simulate irregular motion like coughing.

## 3 Results

We used a standard CamCube TOF camera from PMD Technologies GmbH and observed the phantom movements within a distance of about 1 m. The test setup

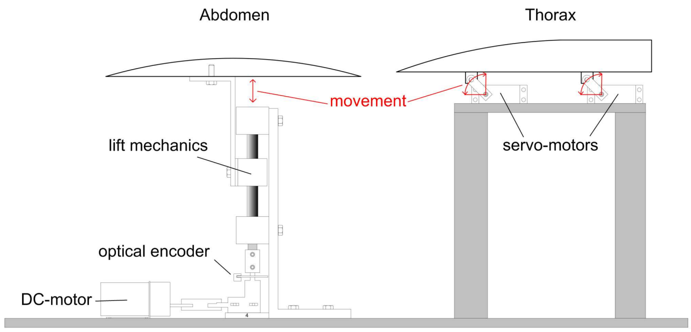



**Fig. 1.** Schematic overview of the mechanical motion of the thorax and the abdomen (sideview).

is illustrated in figure 2. The TOF camera provides a 3-D representation of the shape and motion of the phantom. Using the method introduced by Schaller et al. [4] two independent respiratory signals for thorax and abdomen can be acquired. The phantom is used to evaluate the capabilities of the TOF-based system.

To investigate different respiratory signals the phantom breathing frequency was varied between $3 - 25\,\mathrm{min}^{-1}$, the phantom abdomen and thorax amplitude from $1.3 - 18\,\mathrm{mm}$. The resting respiratory frequency of an adult is $12 - 15\,\mathrm{min}^{-1}$, during stress, e.g. during radiotherapy the respiratory frequency can increase. On the opposite a sedated patient can have a reduced respiratory activity.

After a gain-offset correction of the measured and reference signal the correlation factor according to Pearson was computed. For synchronization purposes, the TOF signal was shifted two timestamps to match the phantom signal. This phase shift is the result of the non-deterministic thread handling in the current operating system. To acquire the two respiratory signals the USB and the serial port of the PC have to be polled simultaneously.

Several measurements were performed. The correlation factors of the TOF and phantom signal varied from 0.36 up to 0.99 depending on amplitude and frequency. Figure 3(a) illustrates a respiratory signal with a high correlation, whereas figure 3(b) shows a lower correlation.

## 4 Discussion

Smaller correlation values, having small peak-to-peak amplitudes, can be explained by the noise of the TOF signal in $z$-direction (Fig. 4(a)). No preprocessing to smooth the TOF data was applied. Therefore, the z-component is noisy. It can be reduced with a mean or bilateral filter, which can increase the correlation and therewith the signal equality of the real respiratory motion and the measured motion. An adequate correlation without filtering can be achieved with a peak-to-peak amplitude of $5\,mm$ and above.

The second parameter of respiratory motion is the frequency. Figure 4(b) shows that the correlation factor can be considered independent of the respira-

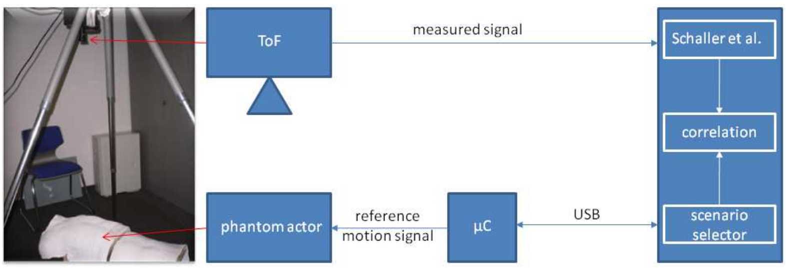


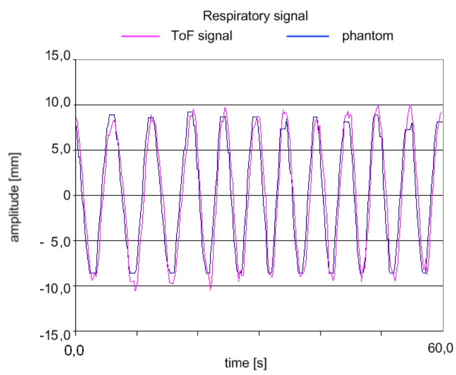

**Fig. 2.** Schematic overview of the test setup for the evaluation of the respiratory gating system. The system can be used to evaluate surface-based motion detection systems.

tory frequency in the range of $3 - 25\,\mathrm{min}^{-1}$. Concluding, the TOF camera can acquire a stable respiratory signal independent from the respiratory frequency with at least 25 breathings per minute.

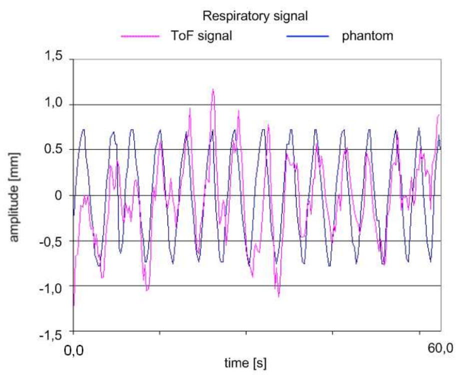
Figure 3(b) shows the limitations of respiratory gating with a TOF camera. Here a breathing amplitude of 1.5 mm peak-to-peak with a respiratory frequency of $14\,\mathrm{min}^{-1}$ was simulated. Thereby a correlation factor of 0.65 was achieved.

The TOF system returned a stable respiratory frequency and a well fitting amplitude signal. With suitable signal post-processing and filtering of the raw data the signal similarity and thereby the correlation can be furthermore increased.

We introduced an anatomic-like breathing phantom which can simulate custom amplitudes and frequencies to generate reference breathing motion signals. The phantom can be used to evaluate surface based respiratory gating or positioning systems accurately. It provides ground truth signals in real-time. As a case study, we evaluated a TOF based respiratory motion detection system and could show in a quantitative manner that it provides reliable data.

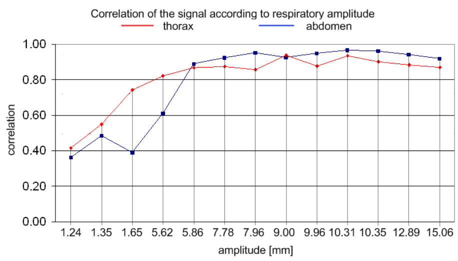



(a) Respiratory frequency of $11\mathrm{min}^{-1}$, amplitude of 17.8 mm, correlation factor of 0.94.

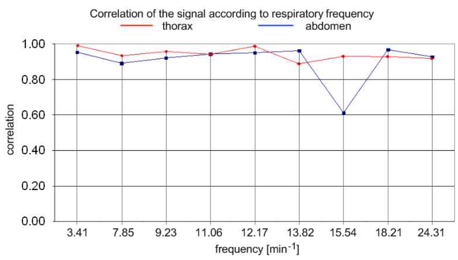



(b) Respiratory frequency of $14\mathrm{min}^{-1}$, amplitude of 1.5 mm, correlation factor of 0.65.

**Fig. 3.** Evaluation of the thorax movement in ToF camera direction.




(a) Amplitudes




(b) Frequency

**Fig. 4.** Correlation factor of the ToF signal and the phantom signal.

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