Novel results in short-range visualization and vision systems based on gated imaging

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Abstract: - Visibility enhancement using gated images has been known for at least 20 years. The majority of gated imaging systems are used to enhance human vision under extremely difficult conditions (fog, turbid water, strong ambient light, etc.). In most of the reported applications the intended ranges of gated-imaging systems are rather long so that a simplified model of gated imaging can be used. Moreover, no attempts have been reported on methods more sophisticated than just capturing images using gated imaging. In this paper, we present selected results expanding areas of typical applications. First, we briefly discuss and explain the theory of short-range gated imaging. In vision-related applications, short-range gated imaging is needed only in high turbidity conditions so that we focus on gated imaging in highly turbid media. Secondly, we propose a technique for automatic image fusion using a sequence of gated images captured by a precisely controlled pulsed laser. The fusion of several images can provide good quality of visualization over a wide range of depths. A feasibility-study system build using this principle will be briefly discussed. We believe that the proposed methods are a significant step towards system capable of providing visibility in extremely difficult scenarios (e.g. inspecting areas of turbulent liquids, seeing through almost non-transparent liquids, etc.).

Key-Words: - gated imaging, image fusion, real-time image processing, high-turbidity vision systems

1 Introduction

Various techniques are available to improve visibility and image quality under difficult conditions. Most of these techniques improve quality of visual data by setting parameters of the capturing devices (e.g. focusing, zooming, etc.) or by post-processing captured images (e.g. contrasting, sharpening, filtering, image fusion, etc.). There are, however, certain techniques that attempt to discriminate the useful optical signals (e.g. signals reflected from the objects that should be visualized) from the visual noise (e.g. backscattering signal from a turbid medium) during the process of image capturing. Gated imaging (also known as burst illumination) that has been developed since 1960's (e.g. [1]) is one of such techniques.

The working principle of gated imaging system is somehow similar to the lidar (Light Detection and Ranging) technology, but with more sophisticated objectives. Lidars capture the returning reflections of illumination signals (laser pulses) to determine (based on time-of-flight computations) distances to targets. Gated imaging systems focus on obtaining the returning reflections of illumination signals in a form of two-dimensional images. Although there are examples of combining both approaches (i.e. correlated images and range maps, e.g. [2], [3]) both techniques are still distinctively different.

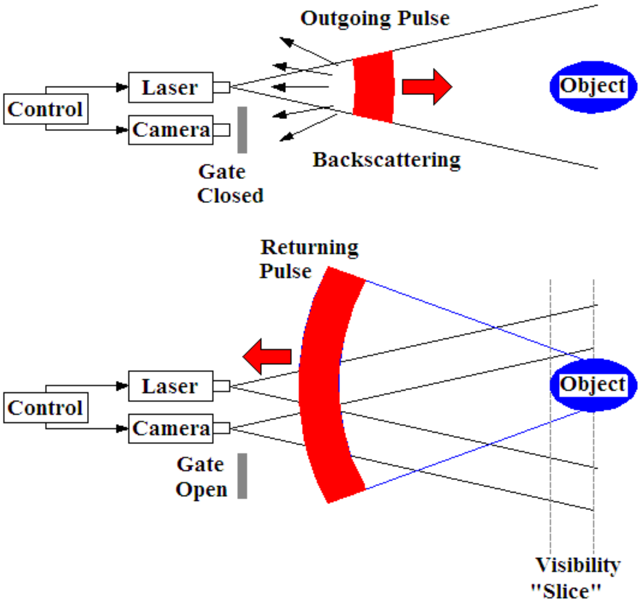

Fig.1. Principles of operation of gated imaging.

The fundamentals of gated imaging are explained in Fig.1. A gated imaging system basically consists of (1) a pulsed laser with its pulses usually diverged into a conical shape, (2) a high-speed gated camera and (3) the control and synchronization circuitry. Projected laser pulses (usually very short, typically several nanoseconds or even less) after reflecting from the present objects, return to a camera with electronically controlled (gated) shutter. If the gate opening is synchronized with the head of the pulse reflected from an object, and closing is synchronized with the pulse tail, the camera captures the image of this object (and other objects positioned within the same range).

Reflections from more distant objects return after the shutter closes (i.e. such objects become invisible) while reflections from foreground objects return before the shutter opens (i.e. such objects appear as dark shadows because no reflected signal is received at the corresponding areas).

Of course, this is an idealized model that neglects at least two important phenomena always existing is the actual environments. First, the ambient illumination may be present so that some "external" visual effects are produced. However, the camera shutter opens for and extremely short period and the intensity of ambient illumination is generally low compared to the laser pulses so that those effects are rather weak. Secondly, reflections from the medium (backscattering) arrive to the camera earlier/later than the useful visual signal. The backscattering effects may be strong (depending on the medium turbidity) but a proper timing of gate opening can remove most of backscattered signals.

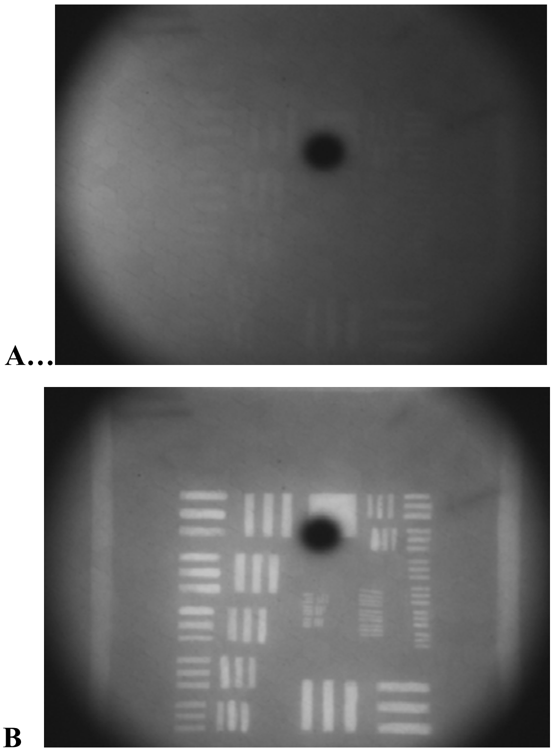

Fig.2. Comparison between a non-gated image (A) and a gated one (B) captured under identical conditions.

Altogether, gated imaging is a very powerful tool for visibility enhancement under visually difficult conditions (e.g. in high-turbidity media and in a presence of strong ambient illumination). As an illustration, a non-gated image is compared to a gated one (both captured in the same high-turbidity medium) in Fig. 2.

In this paper we discuss more advanced issues regarding visibility enhancement by using gated imaging. In particular, the problem of short-range gated imaging is investigated.

Gated imaging at short ranges is required only in extremely turbid media where backscattering effects are so strong that "traditional" visualization produces images containing mostly backscattered signals. In such scenarios, the previous models of gated imaging (e.g. [4], [5]) are too simplified for obtaining good quality gated images. The main problems are: (1) a very low magnitude of useful signals (i.e. reflections from observed objects) compared to backscattered signals and (2) overlapping peaks of both signals. In the following sections we present a theoretical model describing these phenomena, compare the model to experimental results, and finally overview a feasibility-study systems providing significant visibility improvements at short ranges in extremely turbid media.

2 Short-range Gated Imaging

2.1 Modeling reflected signals

Based in the model presented in [6], we developed a mathematical formulation of gated imaging at short ranges in high-turbidity media.

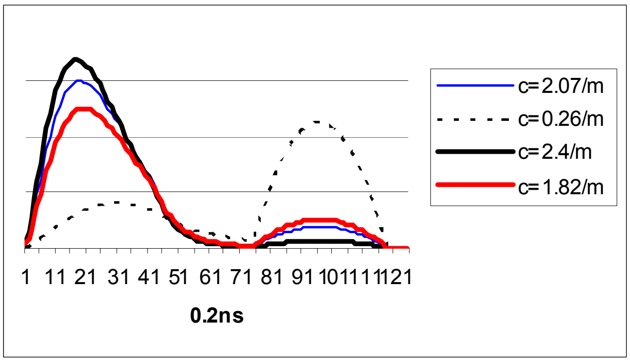

Fig.3. Temporal profiles of the returning signal for a 1.8m target at various attenuations (water turbidities).

Details of the derivations and the resulting formulae are not presented in this paper (they can be found in [7] and other our past papers). Nevertheless, the principles of the model are explained in Fig. 3. The figure shows the computed profiles of the returning signal (reflected from the medium and the object placed at a 1.8m distance) in media of various turbidities (represented by the attenuation coefficient *c*). The profiles have been obtained assuming 9ns effectively length of the laser pulse.

Two peaks in the profiles represent maxima of backscattering (left) and target-reflexion (right). The figure clearly explains why in low-turbidity conditions gated imaging is not required (the reflected signal exceeds backscattering) and in highly turbid media gated imaging is the only way to isolate the useful signal from overwhelming backscattering. The target-reflected signal can be discriminated if the gate opening is synchronized with the return of the right peak (i.e. the target distance should be known).

The model has been confirmed by experiments and the corresponding measured profiles are shown in Fig. 4.

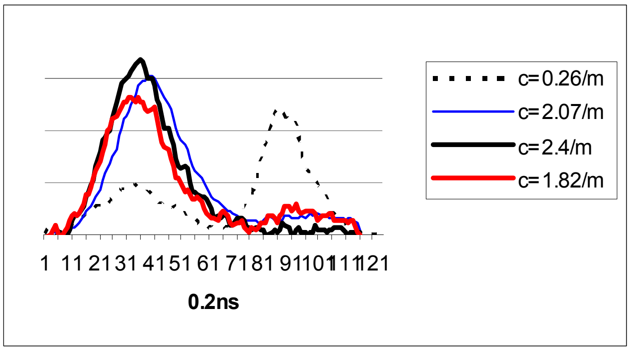

Fig.4. Measured profiles of the returning signal for a 1.8m target at various attenuations.

Measured profiles and their models are qualitatively similar, although there are some differences caused by certain simplifications assumed in the model. The backscattering peaks (the left peaks) in the measured profiles are delayed with respect to their modeled counterparts (especially in high turbidity conditions) because of multiple-scattered photons while the model assumes the backscattering signal formed by single-scattering photons only. Moreover, the shapes peaks are different. This is because the assumed pulse model (convenient for calculations) differs from the actual pulse profiles.

Generally, the proposed model accurately predicts gated imaging results. In particular, if targets are located closer to the system the target-reflected peaks overlap with backscattering peaks. Therefore, there is a natural minimum distance below which it is impossible to discriminate between target-reflected light and backscattering. For example, with 9ns pulses objects can be clearly visualized using gated imaging only if they are further than approx. 1.6m in water or 2.4m in air (the distance depends on the speed of light in the medium).

The problem of even shorter ranges can be solved by reducing the length of illumination pulses. Fig. 5 shows exemplary returning signal profiles calculated for high turbidity conditions (c=2.2/m) with a target at 1.5m distance. The profiles are obtained for 2, 4, 6 and 8ns pulses (all of them carrying the same energy).

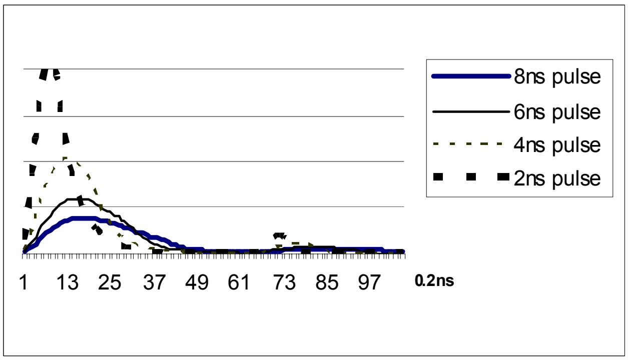

Fig.5. Exemplary profiles for high turbidity conditions with a target at 1.5m distance with four lengths (2, 4, 6 and 8ns) of pulses used.

For shorter pulses the backscattered energy concentrates within the backscattering peak (that return correspondingly earlier). The object-reflected energy is also more concentrated for shorter pulses, but it always (regardless the pulse length) returns at approximately the same time. Therefore, with shorter pulses available, the target-reflected signal can be discriminated from the backscattering noise for targets placed much closer to the device. Thus, shortening the illumination pulses is the fundamental mechanism for obtaining short-range gated imaging visualization systems.

2.2 Camera gating

When the model of range-gated imaging assumes no variation of backscattering effects within the returning signal (e.g. [4], [5] or [8]) the most straightforward method of image capturing is to open the camera gate for the period of time corresponding to the expected return of the target-reflected pulse. In practice, this approach is applicable to imaging object at longer ranges.

At shorter ranges (in particular in high-turbidity media) where the backscattering effect significantly changes with the range change a different approach produces gated images of better quality. An illustrative example is given in Fig. 6 where three options of gate opening are shown (in all cases the gating interval approximately corresponds to the pulse length).

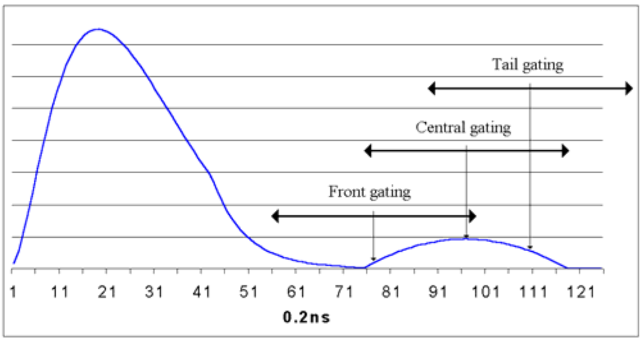

Fig.6. Three gate opening options for a 1.8m target in high turbidity conditions (c=2.07/m).

Our theoretical model predicts that in such scenarios the best *signal-to-noise ratio* (i.e. the best image quality) is obtained for tail gating, i.e. when the gate opening is delayed against the expected return of the object-reflected signal. Experiments confirm the prediction and exemplary results corresponding to Fig. 6 conditions are presented in Fig. 7.

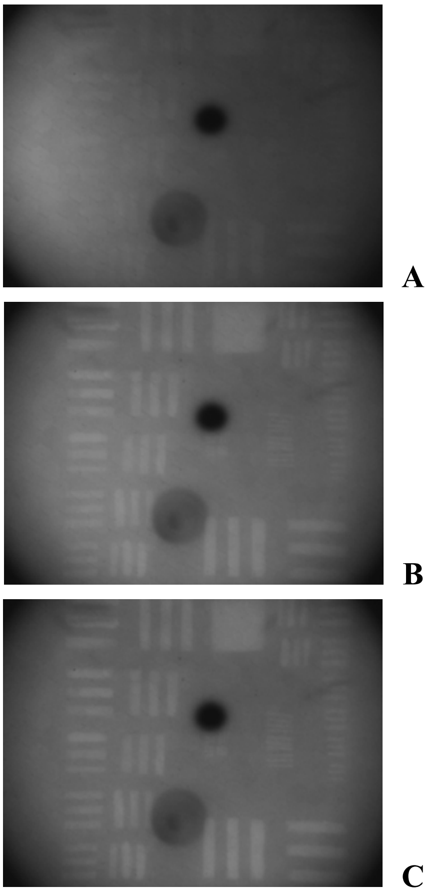

Fig.7. Front-gated (A), central-gated (B) and tail-gated (C) images captured under conditions specified in Fig.

Even though the image in Fig. 7C (tail gating) is darker than in Fig. 2B (central gating) because of lower amounts of accumulated signal, the visual quality of the image is better.

Duration of the gating interval is another factor determining visualization quality in gated imaging. Generally, the gating interval should not be longer than the illumination pulse. Moreover, there is a generally accepted (e.g. [9]) fact is shorter camera gating intervals would produce gated images of higher quality in turbid media. Our results, however, show that higher quality is achievable only if shorter intervals are properly located within target-reflected signal. The intervals should be shifted towards the tail (see Fig. 6) of the expected reflected signal. If the interval shortening is differently located, no significant quality improvement can be expected. More details of this problem are discussed in [7].

3 Image Fusion in Gated Imaging

The results discussed in the previous section clearly show that (if the distance to observed targets can be correctly estimated) gated imaging can produce in highly-turbid media images of much better quality than “traditional” devices. However, when the media turbidity and, correspondingly, the need for gated imaging at shorter range increase, the expected image quality can be achived only if shorter illumination pulses are used. The camera gating time should be adequately reduces as well (even below the duration of illumination pulses) to further improve visibility of objects.

Unfortunately, as explained in Figs 1, 3 and 6, shorter illumination pulses and gating times reduce the “the visibility range” to a very narrow stripe of the observed scenes. In realistic scenarios, the observed scenes may contain numerous objects at diversified (and usually unknown distances). To effectively use gated imaging in high-turbidity media for such cases, novel methods of image formation can be proposed.

Even though a single gated image depicts only a narrow “slice” of the scene, sequences of gated images timed (gated) to continuously changing depths contain enough information to visualize the scene over a wide range of distances. Therefore, a fusion of gated images is the most natural approach to improve visibility in high-turbidity conditions. However, such a method should effectively and relevantly combine visual data from individual gated images to form the fused image.

Two issues are of fundamental importance. First, sequences of gated images should be captured quickly (before the scene content changes) and timing parameters should be accurately modified.

Secondly, the process of actual data fusion from contributing gated images should be adequately designed. In this section we overview both a feasibility-study system developed to solve the first problem, and experimental results of the algorithm tested for the second problem.

3.1 FPGA control of gated imaging

In typical gated imaging systems, the timing parameters are either fixed (defined for a particular application) or set manually in order to obtain the best visibility. However, to quickly capture a sequence of gated images the timing parameters (pulse generation, gate opening delay, etc.) should be updated automatically and with a high level of accuracy.

A feasibility-study system developed for this purpose is based on a laboratory setup consisting of (1) a pulsed laser producing 9ns pulses at up to 20Hz rate, (2) ICCD camera with a high-speed photo-detector (the minimum gating time is approx. 10ns), (3) a delay generator with 5ps resolution to control the camera gating and the laser pulses and (4) the video output path (a frame grabber card and a TV monitor for viewing). The system is attached to a 3 meter water tank (see Fig. 8).

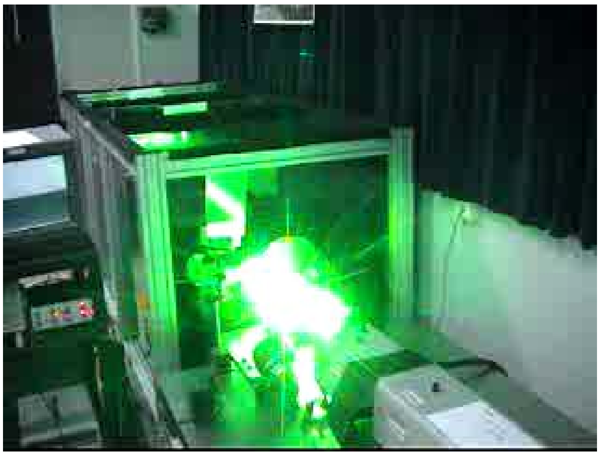

Fig.8. General view and of the laboratory setup.

An FPGA-based controller has been added to the original system to quickly and precisely control pulse trigerring and changes of the gate opening delays. Moreover, in the original setup the camera frame rate and the laser pulsing were not synchronized that resulted in unstable video outputs The FPGA controller incorporates all synchronization functions. Additionally several image processing tasks both in the spatial domain (processing individual gated images) and in time domain (fusion of gated images sequences) are implemented within the controller.

The main component is the Xilinx Spartan-II FPGA (with 200,000 equivalent gates) with 80MHz system clock which is sufficient to synchronize gated image capturing with the video signal path. However, accuracy of the camera gating is limited. 12.5ns clock cycles correspond to 1.4m (in water) or 1.9m (in air) range increment. Such increments are to too long for short-range applications. Thus, the setup acts as a feasibility study only until a higher-frequency (e.g. 400-600MHz) device is available that would allow 0.2-0.25m increments in gated ranges.

Nevertheless, the experimental results have validated our assumptions. Fig. 9 shows a sequence of gated images obtained by delaying the gate opening by one-clock-cycle increments (the minimum increments in a digital controller).

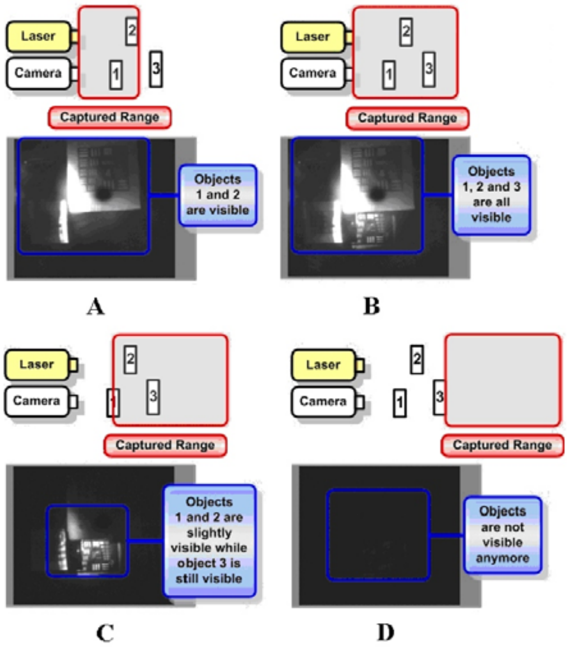

Fig.9. Exemplary effects of delaying camera gating by one-clock-cycle increments.

As an example of other functionalities developed with the FPGA-based controller, Fig. 10 presents principles of ambient light removal. Two gated images (with and without triggering the laser pulse) are captured and subsequently subtracted. The output contains only the object actually present within the gated range of distances.

The most important functionality is, however, the ability to fuse a sequence of gated images (each of them presumably covering only a narrow range of depth) into a single image providing enhanced visibility within a wide range of distances (see the next sub-section).

Details of the FPGA-based controller of gated imaging are discussed in [10].

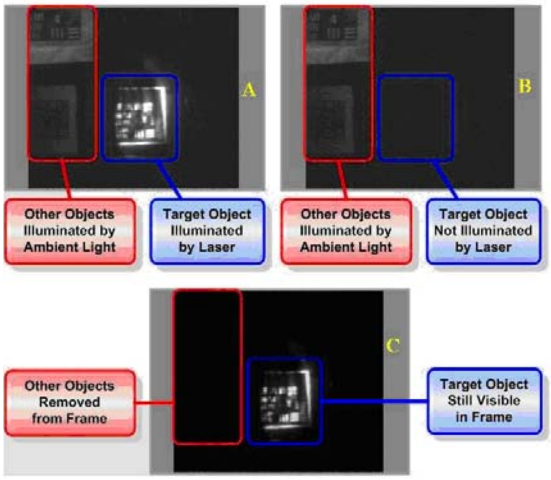

Fig.10. Principles of ambient light removal: an illuminated frame (A), a blank frame (B) and the frame subtraction (C).

3.2 Image-fusion techniques

Scenes containing objects at various depths cannot be visually represented by a single gated image that depicts only a narrow “visibility slice” of the scene. Therefore, a fusion of gated images (timed to various depths) is the most natural approach to enhance visibility in high-turbidity conditions. However, the method would be efficient only if the pieces of visual data are properly extracted from individual gated images to form the fused image.

The most straightforward method, i.e. image fusion by extracting the maximum intensities from individual images, works well only in low turbidities where there is no real need for gated imaging. Much better results can be achieved by exploiting the theory presented in Section 2, i.e. by searching for maxima only after the return of the backscattering peak (see Figs 3 and 4). This method is applicable even at short ranges (because the backscattering peak can be received as early as needed by shortening the illumination pulse – see Fig. 5). Exemplary performances of this method are illustrates in Figs 11 and 12.

In this method, even targets at very short distances and of very low reflectivity could be identified (providing the receiver’s gated camera is sensitive enough). Our experiments have shown feasibility of this method, but it has been also found that the available equipment does not fully satisfy the method’s requirements. The system parameters (in particular, fluctuations of the laser pulses and the dark noise of the camera) have been found inadequate for the accurate fusion of the returning profiles. Nevertheless, improved devices can be expected soon a more practical system could be developed.

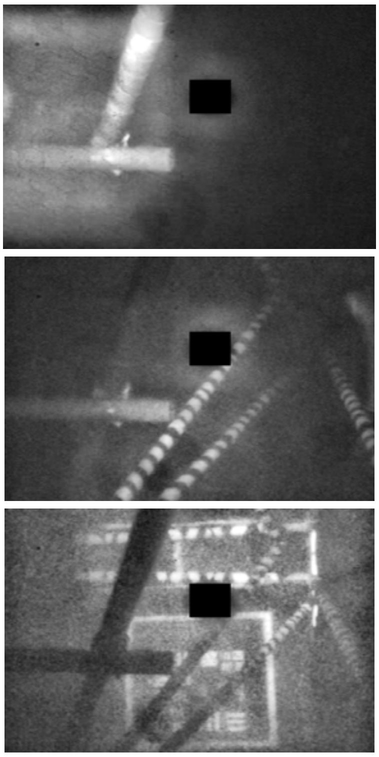

Fig.11. Three gated images captured in high-turbidity water at gradually increased ranges.

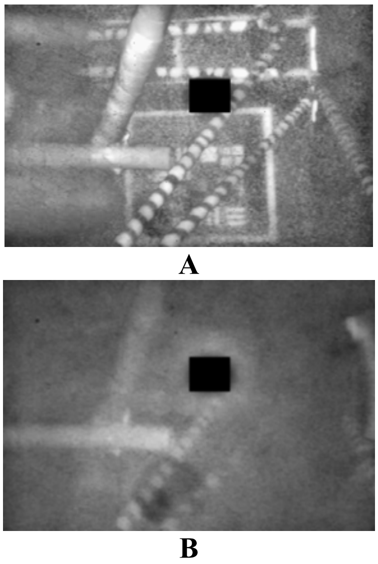

Fig.12. Fusion of Fig. 11 images (A). The same non-gated images shown for reference (B).

4 Conclusion

The most important conclusion is that in short-range applications of gated imaging the duration of the illumination pulses should be reduced. Then, the backscattering peak returns earlier and it is more steep so that closer objects can be visualized but the depth of visualization is limited. We have presnted a technique for an automatic image fusion using a sequence of gated images captured by a precisely controlled pulsed laser. The fusion of several images can provide good quality of visualization over a wide range of depths. A feasibility-study system build using this principle has been briefly discussed. The system is controlled by an FPGA device and controls the gated imaging operation with the accuracy limited by a single clock cycle duration.

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