Ultrasound Image Despeckling/Denoising based on a Novel Multi-Transducer Architecture

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***Abstract*— In the present paper we have focused our efforts in de-noising/despeckling methods for ultrasound images based on a novel multi – transducer architecture. Frequency compounding schemes have been implemented and tested in two different images and the results are compared with the state of the art software based methods for ultrasound image despeckling. Signal – to – noise ratio, SNR, peak – signal – to – noise ratio, PSNR, mean square error, MSE, and the mutual information measures were used to assess the performance of each method. Furthermore, a general scheme for ultrasound image processing based on the notion of superesolution technique that combines multiple low resolution, LR, images of the same scene to produce one high resolution, HR, image, used in camera technology, is proposed. The nature of the system's architecture has made possible the use of simple but effective compounding techniques for speckle reduction while at the same time superesolution approach may produce ultrasound images of better quality and higher resolution. Last but not least, the article provides an insight to the major problems and drawbacks of ultrasound imaging systems and how the proposed architecture is capable of effectively dealing with these problems.**

I. INTRODUCTION

Although ultrasound imaging is one of the most widely used imaging modalities for visualizing internal organs of the human body, the quality of such images is relatively low compared to other modalities such as Magnetic Resonance Imaging (MRI) and Computed tomography (CT) [1]. On the contrary, low cost, portability and accessibility are the main features that have contributed in the popularity and esteem of the modality under consideration. Despite their poor quality, in numerous occasions, ultrasound images may provide vital real – time information about the health state of the subject and can be used instead of MRI or PET [2] and are also an alternative solution in remote areas and places where MRI and CT are unavailable.

Current technology utilizes piezoelectric array transducers, PZT in a wide variety of configurations for 3D and 4D images (real time 3D images). Most of the sensors are attached in a hand held probe guided by radiologists in order to examine the region of interest (ROI) not only for inpatients but also for outpatient [3]. Thus, there is a requirement of real – time machines which poses significant constrains in ultrasound image quality [4]. The acquired images are highly depend on the radiologist skills and perception of the underlying condition each time. In addition, the limited field of view (FOV) of the hand held probes makes the whole procedure of examination slower and prone to human faults and misinterpretations.

The relatively poor image quality is due to low image resolution as well as due to noise that hides image details.

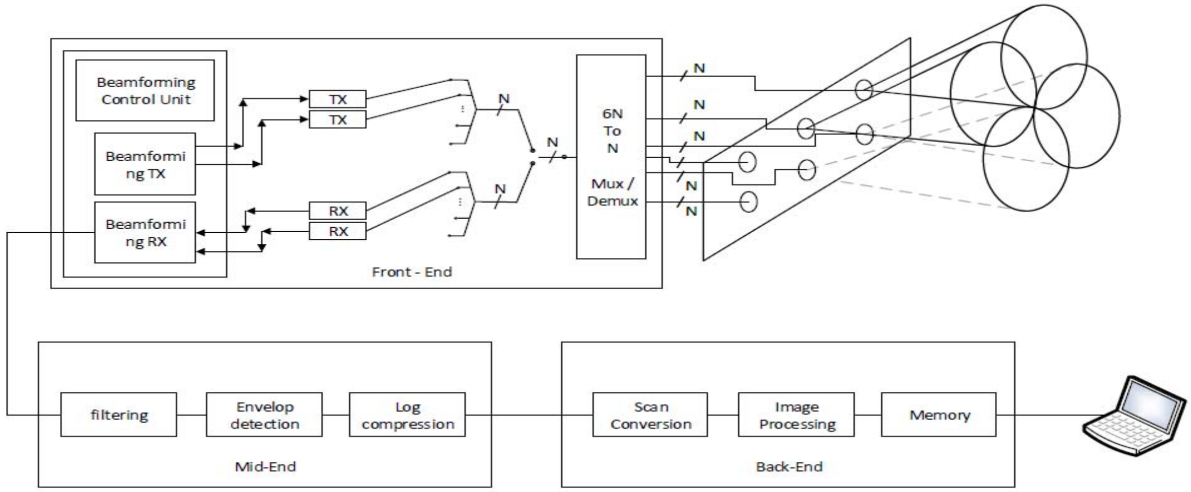

Fig. 1. General architecture of proposed system. Front-end illustrates the integration of the transducers to the board as well as the PSA technique for number of channels reduction.

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Image resolution can vary regarding the type of transducer (linear or phased array), the operating frequency, transducers characteristic [5], beamforming scheme [6] and the frame rate required. Improving image resolution in ultrasound images is an open research area that draws the interest of many engineers. In addition to poor resolution, noise, is present in almost every ultrasound image and is usually known with the term speckle, a multiplicative type of noise formed by the constructive and destructive interference of back scatter signals from objects (scatterers) much smaller than the system's spatial resolution [7]. Speckle reduction is considered of great importance as it can significantly improve human interpretation of ultrasound images and at the same time enhance the overall performance for several image preprocessing and processing tasks (registration, segmentation). Distribution models such as Rayleigh (if number of scatterers per resolution cell is large), Rician and K – distribution (if number of scatterers per resolution cell is large) are extensively used in order to describe speckle noise [8]. Different approaches that effectively deal with speckle noise have been proposed in the literature [9][10][11] and are usually categorized in compounding methods and in post processing methods. Compounding methods either in the spatial or in the frequency domain are based on averaging the information retrieved from multiple images or on applying split spectrum techniques [10] to the original signal. Post processing methods usually apply different types of filtering on the final ultrasound image. Lee, Frost, Kaun, and Weiner filters are the most common ones. Beside those filters, wavelet, curvelet and contourlet based filters have been implemented with great success [12][13][14]. Compounding techniques may be more effective but result in reduced frame ratio and usually require hardware modification and very fast and accurate registration schemes.

In addition to the previously mentioned problems, typical ultrasound images suffer from a wide range of artifacts such as, signals produced from grating lobes, high and low attenuation artifacts and reverberation (equally spaced structures in the final image deriving from the same reflector) [15][16]. Advances in transducer technology tries to depress grating lobes energy compared to the main lobe energy. In order to overcome high and low attenuation artifacts radiologists try to avoid structures such as bones and bubbles of air to achieve a better view of the organ under examination.

The rest of the paper is organized as follow: Section II provides a brief description of the system it's capabilities. The general scheme for producing ultrasound images of higher quality using the underlying architecture is given in section III. In Section IV, a methodology and its first results for denoising/despeckling is presented based on systems configuration presented in section II. Section V concludes the paper.

II. Proposed Architecture And its Capabilities

A. System's Architecture

Based on the system proposed in [17] and illustrated again in Fig. 1, we will examine and investigate how most of the aforementioned limitations can restricted or even addressed.

The system will be composed of an nxm array of circular 2D array transducers integrated into a belt. The hardware of the analog front-end is illustrated for better understanding of the integration of the transducers with the beamforming circuit. The transducers will be placed in such a way to capture the wider possible FOV while at the same time to provide the maximum overlaps. The overlapped regions is the key factor in the supersolution technique. Fig. 1, depicts a typical ultrasound machine with the only difference that the analog mux/demux is necessary for the selection of the appropriate transducer to be active each time. Adopting the PSA method presented in [18] we can further reduce the active channels to k (k<<N). Fig. 1 represents only 2 channels. Each channel will go through filtering, envelop detection and log compression and then will be summed in order to produce the outcome of each sensor through scan conversion procedure. The system could be designed to be as simple as only one transducer to be activated at a time or as quite complex and sophisticated depending on the beamforming scheme. The data acquired from the different sensors will be gathered and stored in the memory. Further image processing techniques will be applied such as registration and stitching to reach the final combined outcome of the entire 3D view of the ROI.

B. System's Features and Capabilities

The proposed configuration for an ultrasound machine will deliver new features and in turn new capabilities in ultrasound imaging. The way that sensors are placed in the belt, the type and number of transducers used is of significant importance. First and foremost the device will maximize the field of view compared to current solutions. The use of 2D phased array transducers will produce the volumetric representation of the tissue – organ under examination automatically and the final outcome will be independent to radiologist's skills. The number and the type of the transducers, on the other hand, will increase the complexity of the system and decrease the frame ratio. At this point we would like to mention that that if the organ under examination doesn't present fast changes then real – time (at least 30 frames per second) imaging is not a requirement. Furthermore, any motion artifacts produced by breath or body movements can be eradicated by combining redundant information of multiple sensors. The particular device has been designed in a manner able to deal with most of the artifact and limitations of current systems.

1) Grating Lobe's Signal

The beam pattern of the transducer and the direction of signal's energy affects a lot the performance of the transducer and the imaging system. If there is a leakage of energy towards other directions than the main one, then structures and boundaries that are present the sidelobes direction may erroneously appear as a signal from the main lobe. Current solutions are based on adjusting the geometry of transducer elements in order to suppress side lobes or utilizing the second or higher order harmonics. With the proposed architecture acquired signals from different sensors can be combined using source localization algorithms or back projection algorithms in order to get rid of the undesired signal coming from grating lobes.

2) High and Low Attenuation Artifact

Most of biological tissues present the same or similar attenuation coefficient with water. This homogeneity has its own merit to the feasibility of ultrasound image creation. Nevertheless, there are certain tissues such as bones that manifest much larger attenuation coefficient compared to soft tissues. The result of beam passing through a bone region is that the most or even whole energy of the beam may be absorbed and everything else beyond this region will appear black in the screen. The opposite effect is encountered when the acoustic beam passes through a region with a very low attenuation coefficient. As a result in this occasion, everything beyond that region may appear very bright making distinguish of boundaries impossible. In general, in both cases all the information that is hidden beyond those regions cannot be revealed. For current ultrasound systems there is not a way to overcome this particular phenomenon but during the scanning process radiologist to try to avoid bones or bubbles of air. The use of more than one transducer to monitor the same region provides the flexibility of recording the ROI from different angles and positions avoiding in this way obstacles such as bones and bubbles and combining retrieved information to produce the whole ROI.

3) De-noising and De-speckling

Almost all ultrasound machines available in the market are equipped with the appropriate software for image de-speckling. Although compounding techniques are considered more effective than software based techniques usually are time consuming due to the fact that require the formation of multiple images, something that is forbidden for real time applications. Spatial compounding requires multiple snapshots of the same scene to be taken from different angles and then all the acquired images need to be registered and averaged in order to produce the final compounded image. Misregistration errors may have the opposite effect in final's image quality. In addition, certain body movements (heart beat and breathing) during the examination may result in a non-linear deformation between consecutive recordings, making the whole registration procedure a challenging task. Frequency averaging technique requires the transmission of acoustic waves of different frequencies but from the same position. By changing the operational frequency the geometry of scatterers inside a resolution cell is changed resulting in turn in a different interference of the beam with the resolution cell. Although such a technique eliminates the registration step it is about a time consuming procedure nearly never adopted in practice. Instead of this, split spectrum processing technique is more often utilized for image despeckling.

The proposed architecture is ideal for applying both frequency and spatial compounding techniques for image denoising/despeckling. The former method frequency compounding may be applied by using a certain transmission frequency from one transducer while all the others are acting as receiving transducers each one in a slightly different frequency. This way, we reduce the overall time of the conventional compounding technique. The drawback in this case is that a registration step is now required as the acquired images are captured from different sensors. Regarding the latter method, the architecture has been designed for it. Taking the advantage of multiple transducers, we are able to capture multiple images of our ROI from different angles and apply the averaging after image registration. Again, the transmission can be performed from one transducer while all the others act as receivers. The best possible combination of spatial and frequency compounding can be adopted in order to produce as possible speckle free images as we can. Despeckling while not losing information is of great importance and can be achieved with the proposed architecture.

4) Improving Image Resolution

The inherent problem of general purpose probes that are composed of phased array transducers is that image resolution is degrading as beam propagates in deeper tissues. That is either due to conical like region scanning or due to beam profile of transducer utilized. A simple approach to improve lateral resolution is to increase the number of scan lines inside the scanning region, resulting in decreasing frame ratio. In addition image resolution is depend on the acoustic frequency utilized. The higher frequency the better the resolution but on the other hand, the higher frequency the less the penetration depth. Thus, arbitrarily increase the frequency will result in undesired effect.

One very interesting technique recently used in camera's technology in order to extract more information about a specific scene recorded by multiple cameras is called super resolution and has become very popular the last decade [19]. With SR, high resolution (HR) images can be produced drilling information from numerous low resolution (LR) images. Super resolution technique seems to be very promising for low quality ultrasound images especially using the proposed architecture. We mentioned earlier that lateral resolution is worsen with respect to the depth. In addition, considering the type of transducers used (phased array transducers) we achieve more overlapping regions as we go deeper inside the human body (Fig. 2). For deeper regions, all sensors may overlap resulting in more images of the region under test. Thus, our intention is to try to compensate the loss of resolution for deeper tissues using the redundant information of those overlapped regions.

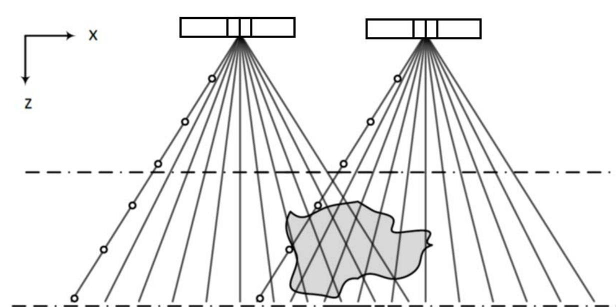

Fig. 2. Overlapping region of two adjacent transducers

In Fig. 2 we may observe that by increasing the overlapped regions we increase the density of pixels per unit area. In order to achieve the maximum density the per unit area all the images of the same area should be slightly.

The first and most important step of super resolution after having the LR images is the registration process. A very accurate registration algorithm is the key in order to maximize the beneficial information that can be extracted from multiple images. The next step is the reconstruction of the High Resolution (mapping on the HR grid) image or the interpolation process. Finally, the last step take cares of any blurring or noise problems encountered by applying a deconvolution method.

III. Proposed Methodology

Herein we describe a methodology based on the proposed architecture with the desire to achieve ultrasound images of higher quality compared to images produced using conventional probes of a stand-alone transducer. The methodology deals with two of the most important limitations of current systems enlisted earlier; speckle noise and low resolution images. To deal with despeckling we perform a combination of frequency and spatial compounding and to deal with low image resolution problem we apply a super resolution algorithm. Problems such as grating lobe's signal or low and high attenuation artifacts are not taken under consideration at this point. All the steps are presented in Fig. 3 and described below.

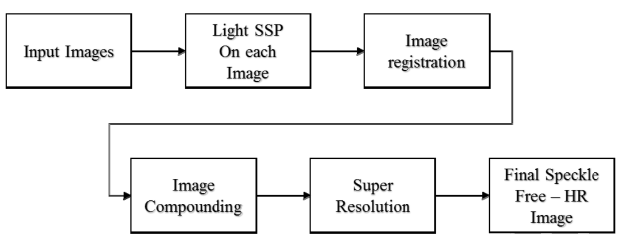

Fig. 3. Proposed methodology for high quality and high resolution ultrasound images

Before proceeding to the actual methodology we need to set the number of independent images that each sensor will acquire. For this particular situation we believe that 5 images per sensor are sufficiently adequate to as most of the systems that are using 5 – 7 images. The methodology implemented is described here:

- We designed the system in such a way that every transducer produces 5 images taken with different operating frequencies around the central frequency. Thus, every sensor will record a certain area and will acquire 5 images of this area. The key characteristic here is that there will be a significant amount of overlap in adjacent transducers.
- One image of the set of 5 images produced from each transducer will go through a mild split spectrum processing. This is not the actual despeckling methodology used. This is done as a quick preprocessing step just before the image registration take place.
- Image registration, as we described earlier is the most important step during the process. We would like to apply a very accurate registration algorithm in order to come up with a compounded image of a better quality rather than ending up with the opposite outcome. In addition a registration algorithm of a subpixel scale will be the basis of super resolution in the final HR image. That is why we first applied the SSP step. Image registration and image segmentation are much more accurate and faster when applied to images that have already undergo noise removal process. Thus, the registration is achieved using only the (nxm) images that have been despeckled through the SSP procedure in order to construct the whole field of view.
- After registering images frequency averaging is applied in every set of 5 images produced by each transducer and the compounded images are stitched together using the outcome of the registration of the previous step.
- The final step is to apply image superesolution technique combining the LR compounded images in order to come up with the final HR image in the overlapped regions. The HR grid can be created for the overlapped regions of the compounded images. After obtaining the HR grid for the overlapped regions a non-uniform interpolation algorithm is applied and then a deconvolution for debluring purposes.

At this point, we would like to mention that although the methodology is generic and is designed for both 2D and 3D images, in our study in the paper we used 2D images.

IV. Preliminary Results On Despeckling

In the following section we performed despeckling in artificial ultrasound images using field II [20] toolbox under matlab's environment. We performed two methods of frequency compounding (simple averaging technique and SSP) on two different images using 1D phased array transducer consisted of 128 elements and scanning the ROI with 86 scan lines with a total field of view 60 degrees. We undertake this comparative study in order to locate the strong and weak point of methods used in literature and to justify our selection of classical frequency compounding. Various performance measures have been calculated for assessing the effectiveness of the despeckling method used each time. We calculated the signal to noise ratio (SNR), the mean square error (MSE) the peak signal to noise ratio (PSNR) found in [21] and the structural similarity measure (SSIM). SSMI measure most of the times is more consistent with human perception about the quality of the image than PSNR or MSE. Apart from the performance measure we visually evaluated the outcome of every method. The formulas for all these measures are presented below:

$$SNR(I(x,y)) = \frac{\mu(I(x,y))}{s(I(x,y))} \tag{1}$$

$$MSE(I(x,y), I_{comp}(x,y)) = \frac{1}{mn}\sum_{x=1}^{x=m}\sum_{y=1}^{y=n}(I(x,y) - I_{comp}(x,y))^2 \tag{2}$$

$$PSNR(I(x,y), I_{comp}(x,y)) = 10\log_{10}(\frac{255^2}{MSE}) \quad (3)$$

$$SSIM(I(x,y) - I_{comp}(x,y)) = \frac{(2\mu_I \mu_{I_{comp}} + c_1)(2\sigma_{I,I_{comp}} + c_2)}{(\mu_I^2 + \mu_{I_{comp}} + c_1)(\sigma_I^2 + \sigma_{I_{comp}}^2 + c_2)} \quad (4)$$

A. Frequency averaging

In order to perform frequency compounding we acquired 5 images of the same scene utilizing 5 different operating frequencies. We applied the above into a phantom of kidney produced by a CT bitmap image. We used two different approaches and the obtained performance measures are presented in Table 1. In the first one we performed the averaging in the 5 produced B-mode images while in the second one we performed the averaging directly in the A – lines and we produced one compound B – mode image. The compounded images are illustrated in Fig. 4.

TABLE 1: FREQUENCY COMPOUNDING METHODS

A.1 Averaging (Images)		
	Kidney	**Kidney** (average 6,6.5,7,7.5,8MHz)
SNR	16.3952	19.7092
MSE		0.0064
PSNR		70.0458
SSIM		0.9998
A.2 Averaging (A - lines)		
	Kidney	**Kidney** (average 6,6.5,7,7.5,8MHz)
SNR	16.3952	25.9533
MSE		0.0273
PSNR		63.7598
SSIM		0.9968

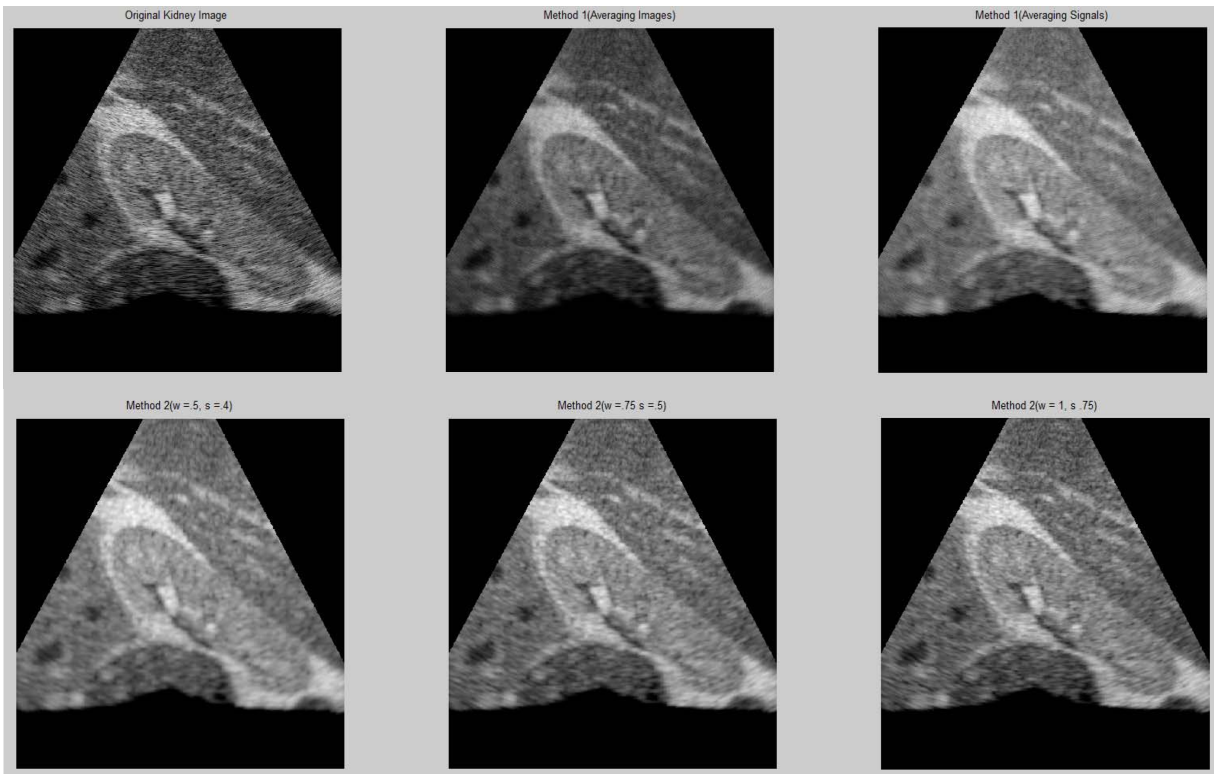

Fig. 4. Obtained results for frequency compounding methods (row 1) and SSP (row 2)

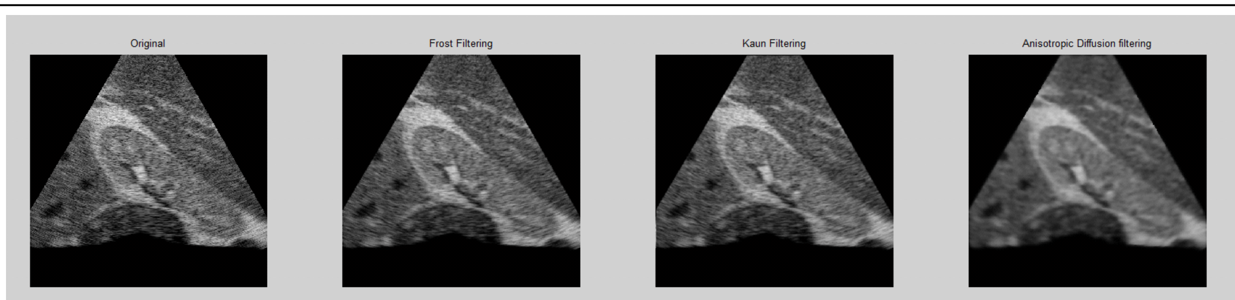

Fig. 5. Obtained results for post-processing filtering methods

B. Split Spectrum Processing

We performed the well-known technique of split spectrum processing using different values of width and separation among the Gaussian – like band pass filters. The total number filters used each time was defined by the effective bandwidth (3 MHz), the width of the Gaussian filter and the separations between two consecutive filters. All the previously mentioned performance measures have been calculated and presented in Table 2 for all the configuration under consideration. The resulted compounded images are given in Fig. 4 in the second row.

TABLE 2: SPLIT – SPECTRUM PROCESSING

B.2 Split Spectrum				
	Original	**(w =.5,s =.4)**	**(w =.75,s= .5)**	**(w =1, s=.75)**
SNR	16.3952	26.5950	24.8419	23.6703
MSE		0.0305	0.0211	0.0156
PSNR		63.2851	64.8913	66.1988
SSIM		0.9963	0.9976	0.9983

As it is observed from Fig. 4. Second row of images as we selecting higher width and separation values the number of Gaussian filters taking place in the procedure is reducing and the smoothing getting lighter. On the contrary, as the number of filters increasing, the SNR is increasing.

C. Post Processing Filtering Methods

In order to acquire a more spherical understanding about the despeckling techniques used from ultrasound machines we collected and implemented few of the most common filters used in literature with the intention to compare them with the compounding methods. We present the results produced using the Frost, Kaun and anisotropic diffuse filters in the same kidney image. Their performance measures are illustrated in Table 3 and the final filtered images are depicted in Fig. 5.

TABLE 3: POST-PROCESSING FILTERING METHODS

2.3 Filtering Methods				
	Original	**Frost**	**Kaun**	**Anisotropic**
SNR	16.3952	18.7304	18.9506	20.8702
MSE		0.0030	0.0042	0.0064
PSNR		64.8913	71.8807	70.0487
SSIM		0.9999	0.9999	0.9998

Although the filters are presented to perform better in terms of performance measures compared to the selected scheme of compounding method, they encounter other problems such as blurring (see anisotropic diffusion filter) and or some loss of information that might be critical especially for medical applications.

V. CONCLUSION

In the paper we presented a novel methodology and scheme based on a specific ultrasound machine for acquiring high quality ultrasound images. The proposed scheme is targeting to deal with numerous well-known limitations of conventional ultrasound apparatus. At this primary state we focused our efforts on denoising/despeckling methodologies and we performed a comparative study in order to highlight the advantages and disadvantages of each one of the methods and to justify our selection of SSP technique as a preprocessing step before the registration technique and our selection of simple frequency averaging for the basic despeckling technique. In addition, the foundations for achieving HR images applying super resolution technique were set. SR, HR images especially for deeper tissues where the degree of overlap is high can compensate the problem of reduced lateral resolution in these depths. Although great efforts have been made all these years towards these direction (improving image quality of ultrasound images), most of the attempts are based on modifying conventional hand-held probes of stand – alone transducers.

REFERENCES

[1] R. Acharya, R. Wasserman, J. Stevens, and C. Hinojosa, "Biomedical imaging modalities: a tutorial," *Comput. Med. Imaging Graph.*, vol. 19, no. 1, pp. 3–25, 1995.

[2] M. H. Wink, H. Wijkstra, J. J. M. C. H. De La Rosette, and C. A. Grimbergen, "Ultrasound imaging and contrast agents: A safe alternative to MRI?," *Minim. Invasive Ther. Allied Technol.*, vol. 15, no. 2, pp. 93–100, Jan. 2006.

[3] F. Lapostolle, T. Petrovic, G. Lenoir, J. Catineau, M. Galinski, J. Metzger, E. Chanzy, and F. Adnet, "Usefulness of hand-held ultrasound devices in out-of-hospital diagnosis performed by emergency physicians," *Am. J. Emerg. Med.*, vol. 24, no. 2, pp. 237–242, Mar. 2006.

[4] O. T. von Ramm and S. W. Smith, "Real-time volumetric ultrasound imaging system," 1990, vol. 1231, pp. 15–22.

[5] K. K. Shung and M. Zippuro, "Ultrasonic transducers and arrays," *Eng. Med. Biol. Mag. IEEE*, vol. 15, no. 6, pp. 20–30, 1996.

[6] K. E. Thomenius, "Evolution of ultrasound beamformers," in *Ultrasonics Symposium, 1996. Proceedings., 1996 IEEE*, 1996, vol. 2, pp. 1615–1622.

[7] R. F. Wagner, S. W. Smith, J. M. Sandrik, and H. Lopez, "Statistics of Speckle in Ultrasound B-Scans," *IEEE Trans. Sonics Ultrason.*, vol. 30, no. 3, pp. 156–163, May 1983.

[8] L. Weng, J. M. Reid, P. M. Shankar, and K. Soetanto, "Ultrasound speckle analysis based on the K distribution," *J. Acoust. Soc. Am.*, vol. 89, no. 6, pp. 2992–2995, Jun. 1991.

[9] T. Joel and R. Sivakumar, "Despeckling of Ultrasound Medical Images: A Survey," *J. Image Graph.*, pp. 161–165, 2013.

[10] S. M. Gehlbach and F. G. Sommer, "Frequency diversity speckle processing," *Ultrason. Imaging*, vol. 9, no. 2, pp. 92–105, 1987.

[11] D. Adam, S. Beilin-Nissan, Z. Friedman, and V. Behar, "The combined effect of spatial compounding and nonlinear filtering on the speckle reduction in ultrasound images," *Ultrasonics*, vol. 44, no. 2, pp. 166–181, Feb. 2006.

[12] A. Khare, M. Khare, Y. Jeong, H. Kim, and M. Jeon, "Despeckling of medical ultrasound images using Daubechies complex wavelet transform," *Signal Process.*, vol. 90, no. 2, pp. 428–439, Feb. 2010.

[13] H. Lazrag and M. S. Naceur, "Despeckling of Intravascular Ultrasound images using curvelet transform," in *2012 6th International Conference on Sciences of Electronics, Technologies of Information and Telecommunications (SETIT)*, 2012, pp. 365–369.

[14] P. S. Hiremath, P. T. Akkasaligar, and S. Badiger, "Speckle reducing contourlet transform for medical ultrasound images," *Int J Compt Inf Engg*, vol. 4, no. 4, pp. 284–291, 2010.

[15] R. Barr, Hindi, and Peterson, "Artifacts in diagnostic ultrasound," *Rep. Med. Imaging*, p. 29, Jun. 2013.

[16] F. W. Kremkau and K. J. Taylor, "Artifacts in ultrasound imaging.," *J. Ultrasound Med.*, vol. 5, no. 4, pp. 227–237, Apr. 1986.

[17] M. Tsakalakis and N. Bourbakis, "A wearable ultrasound multi-transducer array system for abdominal organs monitoring," in *2013 IEEE 13th International Conference on Bioinformatics and Bioengineering (BIBE)*, 2013, pp. 1–5.

[18] J. Johnson, M. Karaman, and B. T. Khuri-Yakub, “Coherent-array imaging using phased subarrays. Part I: basic principles,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 52, no. 1, pp. 37–50, Jan. 2005.

[19] S. C. Park, M. K. Park, and M. G. Kang, “Super-resolution image reconstruction: a technical overview,” *IEEE Signal Process. Mag.*, vol. 20, no. 3, pp. 21–36, May 2003.

[20] J. A. Jensen, “FIELD: A Program for Simulating Ultrasound Systems,” in *10th Nordicbaltic conference on biomedical imaging, vol. 4, supplement 1, part 1:351–353*, 1996, pp. 351–353.

[21] A. M. Eskicioglu and P. S. Fisher, “Image quality measures and their performance,” *Commun. IEEE Trans. On*, vol. 43, no. 12, pp. 2959–2965, 1995.