

Medical imaging equipment is taking on an increasingly critical role in healthcare as the industry strives to lower patient costs and achieve earlier disease prediction using non-invasive means. To provide the functionality needed to meet these industry goals, equipment developers are turning to programmable logic devices such as Altera's FPGAs.

Introduction

Earlier prediction and treatment are driving the fusion of modalities such as positron emission tomography (PET)/computerized tomography (CT) and X-ray/CT equipment. The higher image resolutions that are needed require fine geometry micro-array detectors coupled with sophisticated software/hardware systems for the analysis of photonic and electronic signals. These systems must provide both highly accurate and extremely fast processing of large amounts of image data (up to 250 GMACS and 1 Gbps). Furthermore, to lower patient costs, each piece of equipment must be lower priced and possess a longer life utility. This calls for more flexible systems with the capability to continually update features and algorithms over the equipment's lifetime. Together, flexible algorithm deployment and modality fusion compel the use of programmable system electronic components, such as high-powered CPUs and FPGAs.

Several factors should be considered in the efficient development of flexible medical imaging equipment:

- Development of imaging algorithms requires high-level intuitive modeling tools for continual improvements in digital signal processing (DSP).
- The performance needs for near-real-time analysis require system platforms that scale with both software (CPUs) and hardware (configurable logic). These processing platforms must meet various performance price points and be capable of bridging the fusion of multiple imaging modalities.
- System architects and design engineers need to quickly partition and debug algorithms on these platforms, using the latest tools and intellectual property (IP) libraries to speed their deployment and improve profitability.

With these factors in mind, Altera provides its modular Video and Image Processing (VIP) Suite, a blockset of key IP building blocks that can accelerate the development and implementation of sophisticated imaging algorithms into FPGAs. The VIP Suite blockset, along with other Altera® and partner IP modules and reference designs (including IQ modems, JPEG2000 compression, fast Fourier transform (FFT)/inverse fast Fourier transform (IFFT), edge detection, etc.), provide a broad range of tools designers can use to speed FPGA implementations of computationally intensive tasks.



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Algorithm Developments in Medical Imaging

Some of the most critical pieces of equipment in today's medical development environment include:

- X-ray, magnetic resonance imaging (MRI), CT scanner, ultrasound, and 3D-imaging systems
- Measuring and analysis instruments
- Optical manipulation and analysis
- Surgical microscopes
- Telemedicine systems

Designers are looking for rapid imaging solutions with applications including:

- Image analysis and pattern recognition
- Image enhancement and restoration
- Image and data compression
- Wavelet transform capabilities
- Color space conversion

The following sections cover some of the trends and key developments driving the integration of programmable logic into medical imaging equipment.

Image-Guided Therapy

Intraoperative image processing for surgical guidance uses the registration (correlation) of preoperative (CT or MR) images with real-time 3D (ultrasound and X-ray) images to guide the surgical treatment of disease using non-invasive therapies (ultrasound, MR interventional, and X-ray treatments). Various algorithms have been developed to provide the best registration results for the specific fusion of modalities and therapy types.

Molecular Imaging

Molecular imaging is the characterization and measurement of biological processes at the cellular and molecular level. Its purpose is to detect, capture, and monitor abnormalities that cause disease. To speed the study of symptoms and evaluation of therapies, small animals are used in molecular imaging applications. As a result, all medical imaging modalities are being downscaled to miniature equipment sizes.

Areas of study include data acquisition, image reconstruction, image processing, and analysis. For example, X-ray, PET, and single-photon-emission computed tomography (SPECT) have been combined to map functional, cellular, and molecular images at low resolution onto corresponding anatomy at high resolution, down to 0.5 mm. Miniaturization and algorithm exploration drive the use of FPGAs into these compact system platforms, which help accelerate performance beyond the capabilities of multicore CPUs.

Imaging Algorithms

Image enhancement is commonly performed with convolution (linear) filtering. High-pass filtering enhances the detail in an image, but also makes the noise more visible. Low-pass filtering suppresses the noise at the expense of blurring the detail. Most images contain some areas with detail and other areas without much detail. Linear combination filtering is a technique that enhances detail in the former and reduces noise in the latter, by producing both high-pass and low-pass filtered images and combining them according to a mask.

This technique works because the eye is less sensitive to noise in areas that contain detail. The mask is the smoothed output of a Sobel edge-detection filter. It takes on values near one in areas with detail and values near zero in areas without detail. The linear combination of the high-pass and low-pass filtered images, weighted by the mask, produces an image in which detail has been enhanced, while noise has been reduced.

Video Image Stabilization and Registration (VISAR) is an algorithm for real-time video image stabilization. VISAR was developed to improve the quality of video images beyond simpler horizontal and vertical image registration techniques alone, by accounting for rotational and zooming effects in video data sequences. It co-aligns video image fields by removing the effects of translation, magnification, and rotation. Because VISAR allows the user to combine several video images together, noise can be averaged out among frames. VISAR also smoothes jagged edges found in still images extracted from video, and can correct image jitter to about 1/10th of a pixel.

The VISAR algorithm could potentially be applied to:

- Clarify cell images viewed through a microscope
- Stabilize eye images for retinal study
- Stabilize thermal infrared imaging
- Stabilize camera and body movement during endoscopic surgery
- Stabilize images transmitted for telemedicine
- Improve ultrasounds to correct for body movement when viewing MRI videos

Wavelet transforms is an analytical algorithm that overcomes some of the limitations of Fourier analysis. While Fourier analysis transforms signals from time into the frequency domain, it loses time information. This is why, when looking at a Fourier transform of a signal, it is impossible to tell when a particular event took place. Many imaging signals contain important nonstationary or transitory characteristics: drift, trends, abrupt changes, and beginnings and/or ends of events.

To help acquire event information in signals, Dennis Gabor (1946) adapted the Fourier transform to analyze only a small section of the signal at a time—a technique called windowing the signal. More recently, wavelet analysis was developed using a windowing technique with variable sized regions. Wavelet analysis allows the use of long time intervals for more precise low-frequency information and shorter regions for high-frequency information. Wavelet applications include detecting discontinuities and breakdown points, detecting self-similarity, suppressing signals, denoising signals, denoising images, compressing images, and fast multiplication of large matrices. Altera's VIP and DSP libraries provide key building blocks for wavelet manipulations including scaling, shifting, high-pass/low-pass filtering, I/O decomposition, and reconstruction.

Distributed vector processing is an algorithm that enables faster computations. The S-transform (ST) combines features of the FFT and wavelet transforms, revealing frequency variation over both space and time. Applications include texture analysis and noise filtering. However, ST is computationally intensive, making conventional CPU implementations too slow. This problem is addressed by combining vector and parallel computations for a 25X reduction in processing time. Such computationally intense algorithms can be significantly accelerated using a vector processor in conjunction with parallel computations implemented in FPGAs. (See [Development Tools](#) to learn how Altera products can speed algorithm implementations.)

CT Scanning

PET/CT fusion provides an alternative to software-based image fusion (registration), which is routinely used for the alignment of functional and anatomical images of the brain. For other parts of the body, image registration is more problematic because of differences in patient positioning, scanner bed profiles, and involuntary movement of internal organs. In PET/CT fusion, a scanner acquires both functional and anatomical images during a single imaging session, rather than fusing the images post hoc. The CT images provide essentially noiseless attenuation correction factors for the PET data.

MRI

MRI reconstruction creates cross-sectional images of the human body. Two distinct steps are necessary to reconstruct a 3D volume:

1. 2D reconstruction of each slice via FFT produces slices in gray-level, typically matrices, from the frequency domain data.
2. 3D volume reconstruction creates an interslice distance close to the interpixel distance via interpolation of slices, so that images can be viewed from any 2D plane.

Iterative resolution sharpening uses a spatial deblurring technique based on an iterative inverse filtering procedure that reduces noise while the image structure is refocused. Thus, the overall visual diagnostic resolution of the cross section is significantly improved.

Ultrasound

Despeckling of ultrasound images is possible using lossy compression. Ultrasound speckle is generated by the interaction of various independent scatterers (similar to multipath RF reflections in the wireless domain), and manifests itself as multiplicative noise having a granular appearance. By taking the logarithm of the image, speckle noise becomes additive to the desired signal and can be minimized via lossy wavelet compression using a JPEG2000 encoder. Altera offers partners' IP for JPEG2000 encoding/decoding, as well as a median filter and reference design in the VIP Suite for denoising speckle.

Cardiac motion estimation constitutes an important aid in quantifying the elasticity and contractibility of the heart muscle. Localized areas exhibiting abnormal movements are indicative of ischemic heart regions, where insufficient circulation exists. A developing algorithm includes the quantitative evaluation of elasticity from a series of ultrasound images using spatial-temporal registration techniques to find the deformation field with respect to a reference frame. Key VIP and DSP building block functions applied here include 2D filtering, despeckling, correlation, and smoothing.

Video Imaging

In vascular imaging, the gold standard for many years has been radiopaque contrast angiography from X-ray images of blood vessels, using salt-based contrast agents. Today, CT angiography, time-of-flight/phase contrast MR angiography, and duplex/intravascular ultra-sonography are more commonly used. These techniques involve simultaneous acquisition and registration of optoacoustic and ultrasound images, segmentation of vascular and skeletal images, and the use of correlation-based enhancement filters to reduce false positives when diagnosing lung disorders.

For early detection of cancer using the disease's ability to recruit a new blood supply, the BioScan System™ can be implemented. The BioScan System is based on a sensor called the Quantum Well Infrared Photodetector (QWIP), which is sensitive to temperature changes of less than 0.027° Fahrenheit (0.015° Celsius) and has a speed of more than 200 frames per second. The digital sensor detects the infrared energy emitted from the body, thus "seeing" the minute differences associated with increased blood flow due to cancer. A typical implementation is based on a programmable systolic array implemented with a general-purpose workstation and a special-purpose hardware engine built from FPGAs. The engine can accelerate the core algorithm nearly 1,000 times faster than the rate achieved by a state-of-the-art workstation.

X-Ray Imaging

Reverse Geometry X-radiography Lamography (RGL) was developed by Digiray Corporation to improve image clarity. Unlike conventional X-ray systems, the RGL system places the radiographic object close to the X-ray source. A point detector then captures primary radiation without the image-degrading secondary radiation inherent in standard X-ray systems. By using scintillating crystal imaging detectors with a dynamic range at least 10 times superior to film, the digital image can be enhanced by a wide variety of standard image-processing tools such as averaging, filtering, image subtraction, and edge detection/enhancement. The clarity of RGL may provide X-ray imaging for medical applications including mammography, cardiac imaging, brain surgery, and orthopedics.

Motion correction of coronary X-ray images can help sharpen image results. For example, to minimize the effects of breathing and heart pumping (cardiac-respiratory cycle) during imaging, the motion of a "3D-plus-time" coronary model is projected onto 2D images and used to compute a dewarping function (translate and zoom) to correct for the motion, resulting in clearer images.

Critical Building-Block Functions

Some of the key building block functions required for these sophisticated imaging algorithms include CT reconstruction, which requires interpolation, FFT, and convolution functions. In ultrasound, important processing methods include color flow processing, convolution, beam forming, compounding, and elasticity estimation. General imaging algorithms include functions such as color space conversion, graphic overlays, 2D/median/temporal filtering, scaling, frame/field conversions, de-interlacing and sharpening.

The VIP Suite, along with additional IP and reference designs from Altera and its partners, can accelerate integration of these algorithms onto FPGAs, including those systems with the highest performance and smallest footprints. Before describing the VIP Suite of MegaCore® functions, it is important to consider the development methodology of algorithms and corresponding tools.

Development Tools

Imaging architects use high-level software tools to model various algorithms and results. Image modeling tools, such as the Interactive Data Language, are available from companies like RSI, BIR, and Advanced Digital Imaging Research (ADIR). Another trend is the use of open-source toolkits for image registration, segmentation, and image-guided surgery. These tools are optimized for imaging applications and algorithm development via software, but not for implementation into FPGAs.

Algorithmic development in MATLAB software and system-level design in Simulink software are very common DSP design approaches. For example, ADIR, a research and development organization specializing in digital imaging software and algorithm development, needs flexible tools to create fast and accurate image-processing algorithms. These algorithms define and implement various techniques, manipulate 3D images and statistical data, solve equation sets, and display/document algorithms. ADIR has been using MATLAB as a development tool for over 15 years in its various specialties, including digital image processing, quantitative image analysis, pattern recognition, digital image coding and compression, automated microscopy, forensic image processing, and 2D wavelet transforms. In addition to algorithm development, MATLAB can also simulate the use of fixed-point arithmetic commonly used in FPGAs.

Using MATLAB coupled with Altera's tools—DSP Builder, SOPC Builder, Nios® II CPU development kit, Nios II C-to-Hardware (C2H) acceleration compiler, and Quartus® development suite—designers can accelerate their implementations of designs onto FPGAs. These toolsets enable companies like ADIR to accelerate implementation of algorithms in FPGAs, when CPUs alone are not sufficient.

The DSP Builder Advanced blockset allows high-level Simulink synthesis and also timing-driven optimizations to be used in a MATLAB/Simulink design. Design optimization for meeting the user-specified f_{MAX} or latency—from within a high-level tool such as Simulink—is a feature that is unique to Altera and some vendor tools. Fundamentally, this means that you can set a “dial” to the right f_{MAX} and latency that your system needs, and the DSP Builder tool will take care of the rest. It will add in registers to increase f_{MAX} or parallelize certain critical paths to meet latency constraints. This can eliminate weeks of hand-tweaking the resultant HDL code—instead, with a push of a button, the tweaking is done for you.

To use the automated design flow (shown in [Figure 1](#)), follow these steps:

1. Build the design in Simulink using the building blocks from the DSP Builder Advanced Blockset library.
2. Simulate the design to make sure it conforms to the algorithm. DSP Builder blocks are behavioral and allow for fast simulation. They can also be mixed with traditional Simulink blocks to build a complete design.
3. Set the total system f_{MAX} and or latency within the high-level Simulink design description. DSP Builder analyzes the Simulink design description and generates both HDL code and an optional bitstream for the target FPGA device. It incorporates the timing constraints— f_{MAX} and or latency—and automatically adds in pipeline registers and the required amount of timing division multiplexing to meet the design specification.

Figure 1. DSP Builder Advanced Blockset

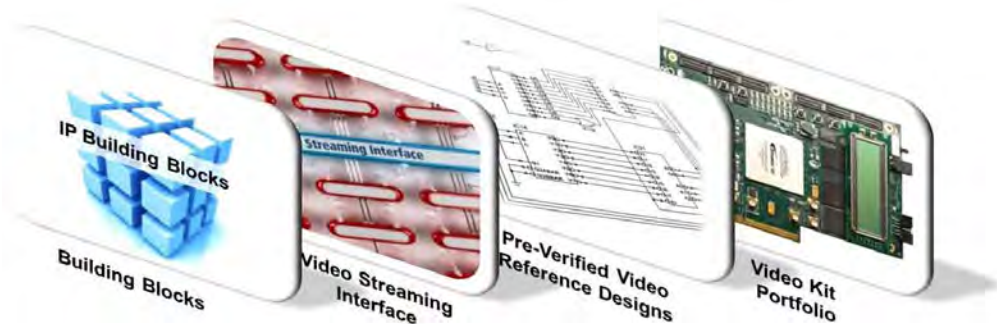


Altera's Video Design Framework

Video processing, especially as the world makes a transition to 1080p HD resolutions, is a natural fit for FPGAs. Altera recognized this transition nearly four years ago and invested in a video design framework to help customers complete their designs faster. The result of this significant engineering investment was the 1080p video design framework, which was awarded the prestigious EDN Innovation Award in 2010.

While other FPGA vendors have a few disparate video functions, Altera is the only vendor that provides a design framework ([Figure 2](#)) with 18 video functions, a streaming video interface standard, over half a dozen hardware-verified reference designs, and a range of video development kits.

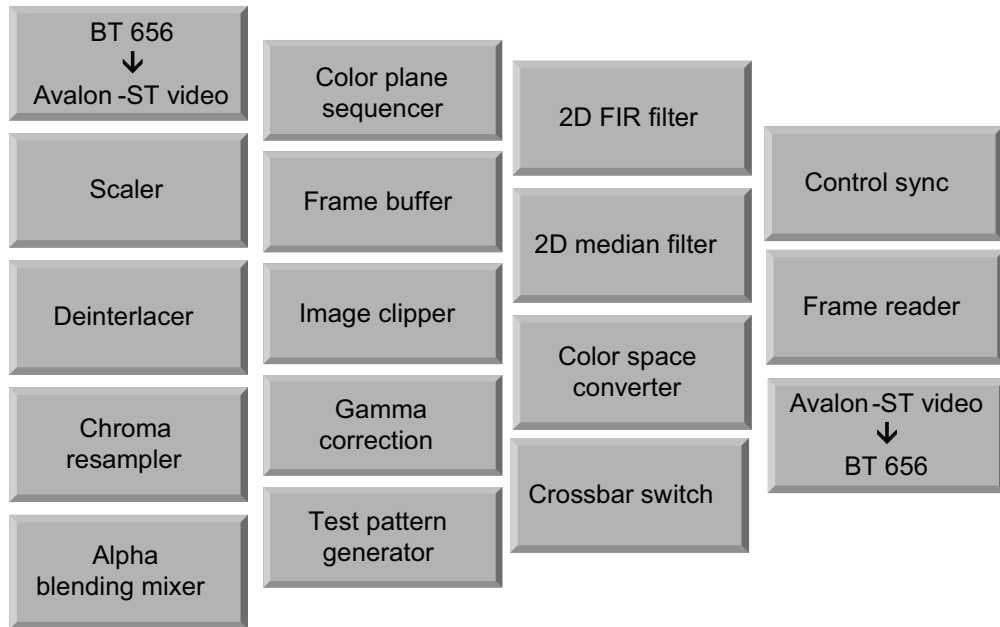
Figure 2. Altera's Video Design Framework



With Altera's video design framework, designers can start with existing working designs, re-use pre-verified IP for common functions such as scaling, de-interlacing, and mixing, add in custom functions, and complete the design in a fraction of the time it would take to develop a new design from scratch.

The key aspect of the video framework is the VIP Suite of 18 commonly used building-block functions, shown in Figure 3, that are used for a variety of different imaging datapaths. The VIP Suite includes functions that range from simple color space converter to highly sophisticated functions for polyphase scaling and motion adaptive de-interlacing.

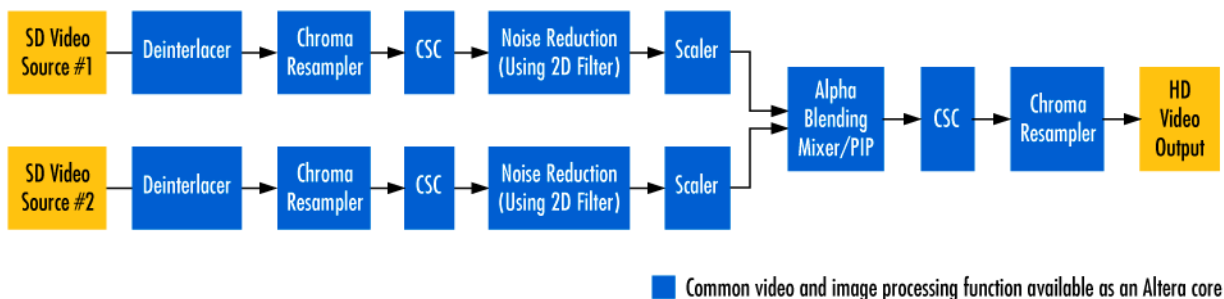
Figure 3. Altera's VIP Suite



Example Video Design

A typical video system using the VIP Suite is shown in Figure 4.

Figure 4. Example Design Block Diagram



Leveraging FPGAs for Medical Imaging

An example of an OEM leveraging Altera devices and tool suites highlights the benefits of FPGA and imaging IP use for today's algorithms and systems.

3D-Computing Inc. developed a breakthrough medical technology called 3D Complete Body Screening (3D-CBS), based on Altera FPGAs. 3D-CBS is expected to revolutionize the use of PET technology by making it safe enough to use for routine preventative-measure patient examinations. 3D-Computing uses Altera devices to accelerate the processing of the algorithms that allow this technology to more accurately examine a patient's body, using only four percent of the radiation they would receive in a traditional PET scan.

Preventive-measure full-body screening of a healthy person using current PET technology is inadvisable because of the dangers of radiation overexposure. Current PET technology is also very slow and costly, making its routine use prohibitive in a time of rising medical costs. Altera FPGAs are used in a variety of ways inside the 3D-CBS system, the most important of which is a matrix of FPGAs that performs the high-speed processing required to more accurately and effectively capture a far greater percentage of the photons emitted from a patient's body during an examination. As a result, the patient's level of radiation exposure is reduced, and image quality is improved.

Key Third-Party Video and Imaging Partners

In addition to the VIP Suite and DSP library, Altera has partnered with multiple suppliers of video and imaging IP, as well as other system suppliers, to help design solutions that meet the requirements of medical-imaging equipment developers.

- ATEME provides H.264 (MPEG-4 AVC) main-profile SD/HD encoding.
- Barco provides JPEG/JPEG2000 encoders/decoders and MPEG-4 advanced simple profile SD encoding.
- BroadMotion provides an efficient JPEG2000 encoder/decoder.
- CAST provides JPEG/JPEG2000 encoders/decoders, MPEG-4 advanced simple profile, and H.264 baseline profiles (SD/HD encoding).
- Simplify Systems Inc. provides a small form factor, 32-channel ultrasound analog front-end receiver module that leverages the performance and low power of their medical reference design used to accelerate time to market for hand-carried and high-performance ultrasound systems.

Conclusion

Baby boomers are seeking new and more accessible therapies, including earlier detection and non-invasive surgical treatments, to treat the most common diseases (especially heart-related ailments and cancer). Advances in the fusion of diagnostic-imaging modalities and their associated algorithm developments are the primary drivers in developing equipment to meet these patient needs. Advanced algorithms require scalable system platforms with significant increases in image-processing performance, yet in smaller, more accessible, portable equipment.

Integrated into multicore CPU platforms, Altera FPGAs provide the DSP horsepower for the most flexible, highest performance systems. To help accelerate the implementation of sophisticated imaging algorithms onto these platforms, high-level development tools and IP implementation libraries are required. Altera developed the VIP Suite with these concerns in mind. The suite contains key building block functions for imaging and is integrated into Altera's complete toolset for rapid development.

Further Information

- 1080p Video Design Framework:
www.altera.com/video_imaging
- Video and Image Processing (VIP) Suite MegaCore Functions:
www.altera.com/products/ip/dsp/image_video_processing/m-alt-vipsuite.html
- Video Processing Reference Design:
www.altera.com/end-markets/refdesigns/sys-sol/broadcast/ref-post-processing.html

Document Revision History

Table 1 shows the revision history for this document.

Table 1. Document Revision History

Date	Version	Changes
July 2010	2.0	<ul style="list-style-type: none"> ■ Updated Critical Building-Block Functions, Development Tools. ■ Added Figure 1, Figure 2, Figure 3. ■ Removed Video and Image Processing Suite. ■ Minor text edits.
April 2006	1.0	Initial release.