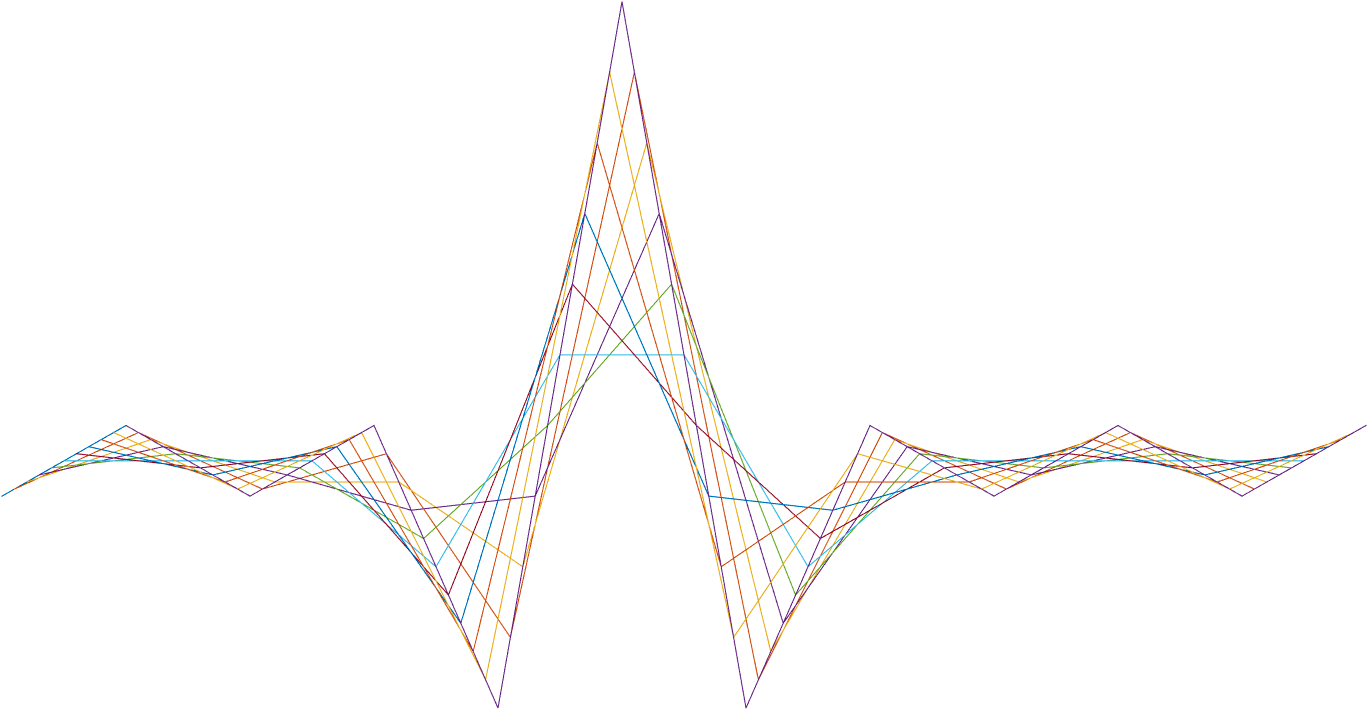
IVCAM2.0 3D Imaging Camera



ASIC A0 JFIL Bilateral filter specification

22 December 2016

Revision 0.6.1

Intel Top Secret

Table 1: Revision history

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Matlab Version | Revision Number | Revised by | Description | Revision Date |
| 2016a | 0.5.0 | Vitaly Surazhsky | Initial release | June 30, 2016 |
| 2016a | 0.5.5 | Vitaly Surazhsky | Spatial and radiometric weights revisited | August 30, 2016 |
| 0.6.37 | 0.6.0 | Vitaly Surazhsky | IR bilateral section added | September 13, 2016 |
| 0.6.37 | 0.6.1 | Vitaly Surazhsky | Test plan added | September 26, 2016 |
| 0.9 | 0.9 | Vitaly Surazhsky | Minor fix in the table of Section 3.1.1. Matlab code is correct (no changes). | January 31, 2017 |

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Introduction

The Bilateral filter smoothes pixel depth and IR values by averaging the values of the 5x5 window around every pixel. The averaging is weighted and takes into account both spatial and radiometric distances (depth or IR differences). The weights are also adaptively configured depending on the pixels’ confidence and/or depth and IR values.

JFIL block consists of three exactly the same bilateral filters working in pipeline one after another (see Figure 1), and one IR bilateral filter. The weights of all the three depth bilateral filters are configured using the same registers, while every depth bilateral filter has its own bypass registers.

Interfaces

Input

1. depth: 16-bit of depth data
2. IR: 12-bit of IR data
3. conf: 4-bits of confidence
4. flags: 4-bit of flags

Output

1. depth: 16-bit of depth data
2. IR: 12-bit of IR data
3. conf: 4-bits of confidence
4. flags: 4-bit of flags

The output of the filter is also passed to the NN filters. The output is controlled by bypass registers and is defined in Section 3.2 of the general JFIL document.

Detailed description

Depth Bilateral filter

The resulting weighted average value of the pixel is computed as follows:

*di* are the pixel values that can be either depth 16-bit values. Weights *wci*, *wri*, *wsi* are defined below.

The sum of nominator and denominator are computed with unsigned integer values. The resulting sums, 42bit=5+8+8+16+5 nominator and 26 bit (for depth) of denominator are then converted for fp32 to perform division in floating point. The resulting fp32 is converted to 16 bit depth output values.

The flags and confidence values are not modified by Bilateral filter. When the input depth value or confidence are zeros, Bilateral filter does nothing and outputs zero (0).

Confidence weights (*wci*)

is the confidence weight that depending on RegsJFILbiltConfMaskD can be either a binary mask or a 5-bit value derived from the pixel 4-bit confidence using LUTJFILbiltConfWeightD. The binary mask is computed by comparing the pixel thresholds with RegsJFILbiltConfThr. The pixel binary mask is set when its threshold is greater or equal than RegsJFILbiltConfThr. If RegsJFILbiltConfMaskD is set that we additionally compute mapping from 4-bit confidence to 5-bit value for every pixel and multiply it by its binary mask.

Spatial weights (*wsi*)

The spatial weights are based on the position of every pixel with the 5x5 windows. Every pixel position gives a different weight. The weights are defined by two dimensional LUTJFILbiltGauss[*ISPAT,* *IPos*] of 32 entries (5 bit) by 6 entries of 8-bit values. The LUT is accessed by two indices *ISPAT* (0..31) and *IPos* (0..5). *IPos* indices are fixed by the pixel position, see Figure 2.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 2 | 3 | 5 | 3 | 2 |
| 3 | 1 | 4 | 1 | 3 |
| 5 | 4 | 0 | 4 | 5 |
| 3 | 1 | 4 | 1 | 3 |
| 2 | 3 | 5 | 3 | 2 |

Figure 2: Spatial indices of the *wsi* weights

*ISPAT* indices are computed based on RegsJFILbiltSharpnessS (6 bit), the confidence and depth of the pixels. There are 4 modes to compute *ISPAT* depending on RegsJFILbiltAdaptS as defined in the table below.

|  |  |
| --- | --- |
| RegsJFILbiltAdaptS | Computation of *ISPAT* |
| 0 | min(31, bitshiftRight(RegsJFILbiltSharpnessS \* 16 \* 16, 8)) |
| 1 | min(31, bitshiftRight(RegsJFILbiltSharpnessS \* LUTJFILbiltConfAdaptS(conf) \* 16, 8)) |
| 2 | min(31, bitshiftRight(RegsJFILbiltSharpnessS \* 16 \* LUTJFILbiltDepthAdaptS(min(255,bitshift(value, -3-RegsGNRLzMaxSubMMExp)), 8)) |
| 3 | min(31, bitshiftRight(RegsJFILbiltSharpnessS \* LUTJFILbiltConfAdaptS(conf) \* LUTJFILbiltDepthAdaptS(min(255,bitshift(value, -3-RegsGNRLzMaxSubMMExp)), 8)) |

Radiometric weights (*wri*)

The radiometric weights are computed as a function *fr*(|*vi* – *vcentral*|). If *vcentral* is not defined (the pixel depth or IR are 0), the bilateral filter output is 0 as well. We first compute clipped to 12bit value difference *dVal* as min(2^12, |*vi* – *vcentral*|).

Each one the three depth bilateral filters uses its own radiometric sharpness registers RegsJFILbiltXSharpnessR, where X is 1, 2, or 3.

The function *fr*(|*vi* – *vcentral*|) is computed as *wri* = *LUTBiltSigmoid*(*IRAD*) depending on RegsJFILbiltAdaptR as defined in the table below:

|  |  |
| --- | --- |
| RegsJFILbiltAdaptR | Computation of *IRAD* |
| 0 | bitshiftRight(min(63, *dVal* \* RegsJFILbiltSharpnessR \* 16 \* LUTJFILbiltDepthAdaptR(0),-12-RegsGNRLzMaxSubMMExp)) |
| 1 | bitshiftRight(min(63, *dVal* \* RegsJFILbiltSharpnessR \* LUTJFILbiltConfAdaptR(conf) \* LUTJFILbiltDepthAdaptR(0),-12-RegsGNRLzMaxSubMMExp)) |
| 2 | bitshiftRight(min(63, *dVal* \* RegsJFILbiltSharpnessR \* 16 \* LUTJFILbiltDepthAdaptR(bitshift(*vcentral*,-8)),-12-RegsGNRLzMaxSubMMExp)) |
| 3 | bitshiftRight(min(63, *dVal* \* RegsJFILbiltSharpnessR \* LUTJFILbiltConfAdaptR(conf) \* LUTJFILbiltDepthAdaptR(bitshift(*vcentral*,-8)),-12-RegsGNRLzMaxSubMMExp)) |

The multiplication of *IRAD* computation is 12bit \* 6bit \* 8bit \* 6bit.

IR Bilateral filter

The IR bilateral filter is very similar to the depth bilateral filter. The main differences are that it does not take into account the pixel confidences, and the IR values are 12 bits.

The resulting weighted average value of the pixel’s IR is computed as follows:

*vi* are 12-bit IR values of the pixels. Weights *wri*, *wsi* are defined below.

The sum of nominator and denominator are computed with unsigned integer values. The resulting sums, 33bit=8+8+12+5 bits of nominator and 21 bit of denominator are then converted for fp32 to perform division in floating point. The resulting fp32 is converted to 16 bit depth or 12 bit IR output values.

Spatial weights (*wsi*)

The spatial weights are defined similarly to the depth bilateral filter. They are based on the position of every pixel with the 5x5 windows. Every pixel position gives a different weight. The weights are defined by two dimensional LUTJFILbiltGauss[*ISPAT\_IR,* *IPos*] of 64 entries (6 bit) by 6 entries of 8-bit values. The LUT is accessed by two indices *ISPAT\_IR* (0..63) and *IPos* (0..5). *IPos* indices are fixed by the pixel position, see Figure 2.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| 2 | 3 | 5 | 3 | 2 |
| 3 | 1 | 4 | 1 | 3 |
| 5 | 4 | 0 | 4 | 5 |
| 3 | 1 | 4 | 1 | 3 |
| 2 | 3 | 5 | 3 | 2 |

Figure 2: Spatial indices of the *wsi* weights

*ISPAT* indices are computed based on RegsJFILbiltSharpnessS (6 bit) and the IR values pixels. There are 2 modes to compute *ISPAT* depending on RegsJFILbiltAdaptS as defined in the table below.

|  |  |
| --- | --- |
| RegsJFILbiltIRAdaptS | Computation of *ISPAT\_IR* |
| 0 | bitshiftRight(min(31, RegsJFILbiltIRSharpnessS \* 16,-4)) |
| 1 | bitshiftRight(min(31, RegsJFILbiltIRSharpnessS \* LUTJFILbiltIRValueAdaptS(bitshift(value, -6)),-4)) |

Radiometric weights (*wri*)

The radiometric weights are computed as a function *fr*(|*vi* – *vcentral*|). We first compute clipped to 12bit value difference *dVal* as |*vi* – *vcentral*|.

The function *fr*(|*vi* – *vcentral*|) is computed as *wri* = *LUTBiltSigmoid*(*IRAD*) depending on RegsJFILbiltIRAdaptR as defined in the table below:

|  |  |
| --- | --- |
| RegsJFILbiltAdaptR | Computation of *IRAD* |
| 0 | bitshiftRight(min(63, *dVal* \* RegsJFILbiltIRSharpnessR \*  LUTJFILbiltIRDepthAdaptS (63),-11)) |
| 1 | bitshiftRight(min(63, *dVal* \* RegsJFILbiltIRSharpnessR \* LUTJFILbiltIRDepthAdaptS(bitshift(*vcentral*,-6)),-11)) |

The multiplication of *IRAD* computation is 12bit \* 6bit \* 8bit \* 6bit.

Memories and computations

Every bilateral filter block works on 5x5 pixel patches and thus requires 4 line buffers. Three combined depth and IR bilateral filters require 12 line buffers.

Table 2: LUTs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Name | Entries | Entry size | Fixed | Description |
| LUTJFILbiltConfAdaptS | 2^4 | 5 | no | Adaptive spatial confidence weights |
| LUTJFILbiltDepthAdaptS | 2^8 | 5 | no | Adaptive spatial depth weights |
| LUTJFILbiltIRValueAdaptS | 2^6 | 5 | no | Adaptive spatial IR weights |
| LUTJFILbiltConfAdaptR | 2^4 | 6 | no | Adaptive radiometric confidence weights |
| LUTJFILbiltDepthAdaptR | 2^8 | 8 | no | Adaptive radiometric depth weights |
| LUTJFILbiltIRValueAdaptR | 2^6 | 8 | no | Adaptive radiometric weights for IR |
| LUTJFILbiltGauss | 6\*2^5 | 8 | no | Spatial weights (Gaussian) |
| LUTJFILbiltSigmoid | 2^6 | 8 | no | Sigmoid for radiometric weights |
| LUTJFILbiltConfWeightD | 2^4 | 5 | no | Confidence weights |

Registers

Table 2: Registers

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Name** | **Size** | **Default** | **Range** | **Special values/ description** |
| **General** |  |  |  |  |
| RegsGNRLImgHsize | 12 | 640 | 1-1280 | Horizontal resolution |
| RegsGNRLImgVsize | 12 | 480 | 1-960 | Vertical resolution |
| RegsGNRLzMaxSubMMExp | 3 | 3 | 0..7 | Sub-mm precision exponent of the depth dynamic range |
| **JFILBilt** |  |  |  |  |
| RegsJFILbiltConfMaskD | 1 | 1 | 0,1 | 0: confidence is 1 bit mask  1: confidence is 5 bit value + mask |
| RegsJFILbiltConfMaskIR | 1 | 1 | 0,1 | 0: confidence is 1 bit mask  1: confidence is 5 bit value + mask |
| RegsJFILbiltConfThr | 4 | 2 | 0..15 | The confidence threshold |
| RegsJFILbiltAdaptS | 2 | 1 | 0..3 | Spatial adaptive depth mode:  0: not adaptive  1: confidence based  2: depth based  3: confidence and depth based |
| RegsJFILbiltAdaptR | 2 | 1 | 0..3 | Radiometric adaptive depth mode:  0: not adaptive  1: confidence based  2: depth based  3: confidence and depth based |
| RegsJFILbiltIRAdaptS | 1 | 1 | 0,1 | Radiometric adaptive IR mode: 0: not adaptive  1: IR value based |
| RegsJFILbiltIRAdaptR | 1 | 1 | 0,1 | Spatial adaptive IR mode: 0: not adaptive  1: IR value based |
| RegsJFILbiltSharpnessS | 6 | 16 | 0..63 | Spatial sharpness for depth |
| RegsJFILbiltIRSharpnessS | 6 | 16 | 0..63 | Spatial sharpness for IR |
| RegsJFILbilt1SharpnessR | 6 | 16 | 0..63 | Radiometric sharpness of bilt**1** |
| RegsJFILbilt2SharpnessR | 6 | 16 | 0..63 | Radiometric sharpness of bilt**2** |
| RegsJFILbilt3SharpnessR | 6 | 16 | 0..63 | Radiometric sharpness of bilt**3** |
| RegsJFILbiltIRSharpnessR | 6 | 16 | 0..63 | Radiometric sharpness of bilt**IR** |
| RegsJFILbilt1Bypass  RegsJFILbilt1NNBypass | 1 | 0 | 0,1 | Bypass of the 1st depth filter |
| RegsJFILbilt2Bypass RegsJFILbilt2NNBypass | 1 | 0 | 0,1 | Bypass of the 2nd depth filter |
| RegsJFILbilt3Bypass RegsJFILbilt3NNBypass | 1 | 0 | 0,1 | Bypass of the 3rd depth filter |
| RegsJFILbiltIRBypass RegsJFILbiltIRNNBypass | 1 | 0 | 0,1 | Bypass of the IR filter |

Test plan

|  |  |  |
| --- | --- | --- |
| **Name** | **Values** | **Distribution** |
| RegsJFILbiltConfMaskD  RegsJFILbiltConfMaskIR | 0 | 50 |
| 1 | 50 |
| RegsJFILbiltAdaptS  RegsJFILbiltAdaptR | 0 | 20 |
| 1 | 25 |
| 2 | 25 |
| 3 | 30 |
| RegsJFILbiltIRAdaptS  RegsJFILbiltIRAdaptR | 0 | 40 |
| 1 | 60 |
| RegsJFILbiltConfThr | 0 | 5 |
| 1..3 | 40 |
| 4..6 | 30 |
| 7..15 | 25 |
| RegsJFILbiltSharpnessS  RegsJFILbiltIRSharpnessS  RegsJFILbilt1SharpnessR  RegsJFILbilt2SharpnessR  RegsJFILbilt3SharpnessR | 0..3 | 5 |
| 4..15 | 25 |
| 16 | 30 |
| 17..31 | 25 |
| 32..63 | 15 |
| RegsJFILbilt1Bypass  RegsJFILbilt1NNBypass  RegsJFILbilt2Bypass  RegsJFILbilt2NNBypass  RegsJFILbilt3Bypass  RegsJFILbilt3NNBypass  RegsJFILbiltIRBypass  RegsJFILbiltIRNNBypass | 0 | 5 |
| 1 | 95 |