Implementation of algorithm for extension of unambiguous distance measurement of 3D ToF Cameras using Simulink and HDL Coder

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- Amit Nahar
Agenda

- **Problem Statement**
- Why 3D?
- Issue with Distance Calculation using single modulation frequency
- Unambiguous Distance Extension using two modulation frequency
- Complexity of Algorithm
- Current workflow & Proposed workflow
- How Simulink - HDL Coder is useful for Implementation
- Conclusion
Problem Statement

● Time to market is very important for any product for its success.

● To achieve this goal, design should be generic and easy to upgrade without much modification.

● RTL development cycle is very time consuming and expensive.

● For fixed point arithmetic implementation, accuracy and precision play vital role to produce expected result in real time.

● To cope up with above problems, we have decided to implement ‘Distance Calculation’ algorithm on Simulink-HDL coder.
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Why 3D?

**loss of depth information:**

Conventional cameras detect the brightness of the environment. Due to projection of an image, depth information of the scene is lost.

**acquisition of depth information:**

The Time-of-flight 3D camera detects additionally to the brightness the complete spatial information of the scene. The depth information can be depicted with colored code. (red = 'near'; blue = 'far')
Range Imaging Techniques

- Range Imaging techniques
  - Triangulation
    - Stereo
    - Sheet of Light
  - Structured Light
  - Time of Flight
    - LIDAR
    - PMD
  - Coded Aperture
Time of Flight principle
Calculation of distance and amplitude

Distance -

\[ \Phi = \tan^{-1} \left( \frac{r(\tau_{270}) - r(\tau_{90})}{r(\tau_0) - r(\tau_{180})} \right) \]

\[ d = \left( \frac{c \cdot \Phi}{4 \pi f_{mod}} \right) = \left( \frac{3 \cdot 10^8 \cdot 2\pi}{4 \pi \cdot 40 \cdot 10^6} \right) = 3.75 m \]

Amplitude -

\[ A = \frac{\sqrt{[r(\tau_{270}) - r(\tau_{90})]^2 + [r(\tau_0) - r(\tau_{180})]^2}}{2} \]

where,

\( r(\tau_N) \) is the correlation sample for phase N
\( c = \) speed of light
\( f_{mod} = \) modulation frequency
\( \Phi = 0 \) to \( 2\pi \)
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Issue with Unambiguous Distance Calculation using single modulating frequency

- Distance is rolled over after range ‘d’.

**Figure 1**: Due to phase wrapping of the returned illumination signal, objects beyond the maximum unambiguous range, $d_u$, appear to be closer than they really are.
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Figure 2: A target measured twice using different modulation frequencies. Each measurement gives a set of possible object locations, and the true location is determined by where the two measurements are in agreement.

\[
dE = \left( \frac{c}{2 \times GCD(f_a, f_b)} \right) = \left( \frac{3 \times 10^8}{2 \times 10^6} \right) = 150m
\]

Where \( f_a = 40MHz \), \( f_b = 41MHz \)
Unambiguous distance using two modulating frequency

\[ d = \left( \frac{dE}{M_a \times M_b} \right) \times (M_a \times k_b + M_a \times \varphi_b + w \times (e - \text{round}(e))) \]

\[ dE = \left( \frac{c}{2 \times GCD(f_a, f_b)} \right) \]

\[ e = (M_b \times \varphi_a - M_a \times \varphi_b) \]

\[ k_b = \text{mod}(k_0 \times \text{round}(e), M_b) \]

- \( c \) is speed of light (\( 3 \times 10^8 \) m/s)
- \( f_a \) and \( f_b \) the 2 frequencies, which are factors of co prime ratios \( M_a \) and \( M_b \)
- \( \varphi_a \) and \( \varphi_b \) are the phase delays with frequencies \( f_a \) and \( f_b \)
- \( k_0 \) is such that \( \text{mod}(k_0 \times M_a, M_b) = 1 \)

Ref: Development of a Compact, Configurable, Real-time Range Imaging System by Adrian Peter Paul Jongenelen
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Complexity of Algorithm

- Multiplications : 6
- Additions /Subtractions : 2/2

- Bit width of each signal

\[ d = \left( \frac{dE}{M_a \times M_b} \right) \times (M_a \times k_b + M_a \times \varphi_b + w \times (e - \text{round}(e))) \]

\[ 8.8 = (8.16) \times (8.0 \times 8.0 + 8.0 \times 3.13 + 0.2 \times (8.16 - 8.0)) \]
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## Current Workflow & Proposed Workflow

### Time Spent for FPGA Implementation

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<th>Current Workflow</th>
<th>Proposed Workflow</th>
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<tr>
<td>Design Document</td>
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<tr>
<td>Detailed Design</td>
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<td>1</td>
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<td>HDL Creation</td>
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<td>PnR Simulation</td>
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### Resource Comparison

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<th>Simulink - HDL Coder</th>
<th>Hand Written Code</th>
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<tr>
<td>Number of Slice Registers</td>
<td>324</td>
<td>412</td>
</tr>
<tr>
<td>Number of Slice LUTs</td>
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<td>1241</td>
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<td>Number of fully used LUT-FF pairs</td>
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<td>189</td>
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<tr>
<td>Number of DSP48A1s</td>
<td>8</td>
<td>12</td>
</tr>
</tbody>
</table>

Resource Comparison Simulink - HDL Coder

Resource Comparison Hand Code
Role of Simulink & HDL Coder

- Fixed point implementation is simpler as compared to hand-written code
- Back annotation for critical timing analysis
- Resource Sharing
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Conclusion

- Development time reduced
- Traceability Between HDL Code & Simulink Model
- Testing & Verification time reduced
- Resource utilization is less than hand-written code
THANK YOU