Testbed for On-Board Signal Processing (one year with signal processing folks)

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in conclusion …

After a12-month study of Signal Processing Folks , I reached the conclusion that they are comfortable with:

$$P(\alpha,\beta,\theta) = \vec{w}'(\alpha,\beta,\theta)S(\omega)\vec{w}(\alpha,\beta,\theta)$$

$$\vec{w}(\alpha,\beta,\theta) = \frac{1}{M}\begin{bmatrix} \exp[jk_0\sin(\alpha)x_1(\theta) + j2\pi k_0\sin(\beta)y_1(\theta)] \\ \dots \\ \exp[jk_0\sin(\alpha)x_M(\theta) + j2\pi k_0\sin(\beta)y_M(\theta)] \end{bmatrix}$$

$S(\omega)$ = Cross Spectral Density Matrix at 7 kHz

matrices, FFT, the greek language …

```
% fourier vector
K = exp(i*bf.OmegaTau*[1:bf.SamplesPerSnapshot]')/(bf.SamplesPerSnapshot);

% csd computation
CSD = zeros(bf.NbElements,bf.NbElements);
for s=1:bf.SnapshotsPerFile
   X = x(:,(s-1)*bf.SamplesPerSnapshot+[1:bf.SamplesPerSnapshot]) * K;
   CSD = CSD + X*X';
end
CSD = CSD /bf.SnapshotsPerFile;

% beamforming
BFO = zeros(bf.NbAzimuths,bf.NbElevations);
for az = 1:bf.NbAzimuths
   for el = 1:bf.NbElevations
      V = bf.SteeringVector{az,el};
      BFO(az,el) = real(V'*CSD*V);
   end
end
```

Matlab

but they seem to have a harder time with …

```
#include <iostream>
#include <complex>
#include <cmath>
#include "CBeamFormer.h"

static cdouble ScalarProduct_cr(cdouble* X, double* Y, int N);
static void AddOuterProductToMatrix(cdouble* X, cdouble**A, int N);
static cdouble MatrixProjection(cdouble** A, cdouble* X, cdouble* Y, int N);
static cdouble** MatrixNew(int M, int N);
static void MatrixZero(cdouble** A, int M, int N);

using namespace std;
//FILE* fid;

}
```

```
//================================================
//==============PUBLIC METHODS====================
//================================================
CBeamFormer::CBeamFormer(int NbElements, double ElementSpacing, double SamplingRate, double BeamformFrequency, double
SpeedOfSound, double BeamSpacing, int SamplesPerSnapshot)
{
                double* Window = new double[NbElements];

                m_kd = (2*M_PI*BeamformFrequency/SpeedOfSound)*ElementSpacing;
                m_SamplesPerSnapshot = SamplesPerSnapshot;
                m_NbElements = NbElements;

                for (int n=0 ; n < NbElements ; n++)
                                Window[n] = 0.54-0.46*cos(2.0*M_PI*n/(NbElements-1));

                m_NbAngles = int(180.0/BeamSpacing);
                m_CosAngles = new double[m_NbAngles];
                for (int n = 0 ; n<m_NbAngles ; n++)
                                m_CosAngles[n] = cos((M_PI/180.0*BeamSpacing)*n);
                m_BFO = new double[m_NbAngles];

                // create the detection filter (i.e. the fourier transform vector)
                m_Detector = new cdouble[SamplesPerSnapshot];
                double OmegaTau = 2*M_PI*BeamformFrequency/SamplingRate;
                for (int n=0 ; n < m_SamplesPerSnapshot ; n++)
                                m_Detector[n] = exp(cdouble(0.0,OmegaTau*n))/double(m_SamplesPerSnapshot);

                // create the steering vectors
                m_Steering = MatrixNew(m_NbAngles,NbElements);
                for (int m=0 ; m < m_NbAngles ; m++)
                {
                                for (int n=0 ; n < NbElements ; n++)
                                                m_Steering[m][n] = Window[n] * exp(cdouble(0.0 ,
(m_kd*m_CosAngles[m])*n));
                }

                // create the csd
                m_CSD = MatrixNew(NbElements,NbElements);
                MatrixZero(m_CSD,NbElements,NbElements);

                delete[] Window;

}
```

C/C++

Krolik's SAM lab

- **Jeff Krolik's Sensor Array and Multipath Signal Processing Laboratory (Duke University):**
  - sonar/radar array processing
  - multipath
  - tracking in clutter
  - left-right disambiguation, etc
- **Traditional approach**
  - get a data set from a cruise
  - process in Matlab
- **Got tougher lately**
  - proprietary & classified data
- **New paradigm**
  - buy hardware to generate own data
  - ex: "floor" robot + 64-element microphone array.

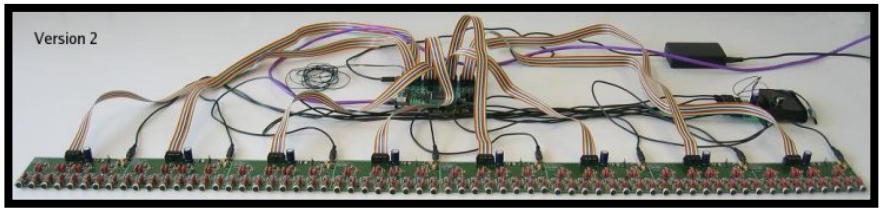
Acoustic Hardware

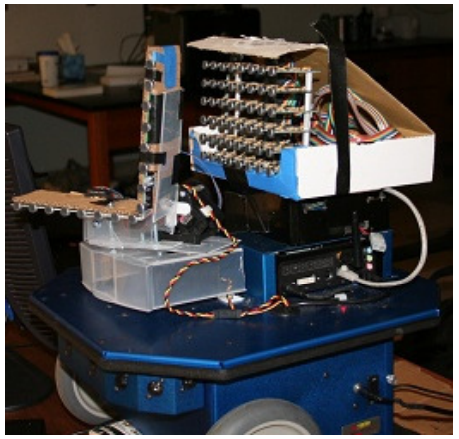
- **Videre robot**
  - independent speed/turn rate control
  - pan-tilt actuators
  - 8 sonar ranges
  - odometry
  - lidar (Hokuyo URG,5m range)
  - Linux PC
  - sound card
  - WiFi
- **8 x 8 microphone array**

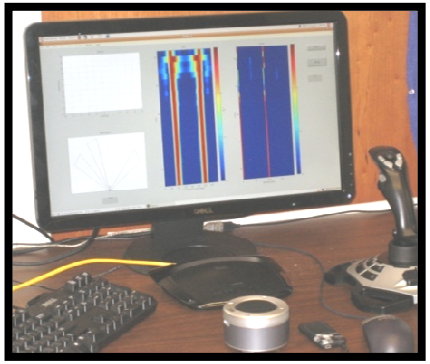
  NIST,

  re-configurable: forward facing, towed, 2D, variable geometry, etc.
- **command&control**

  Matlab-based, joystick



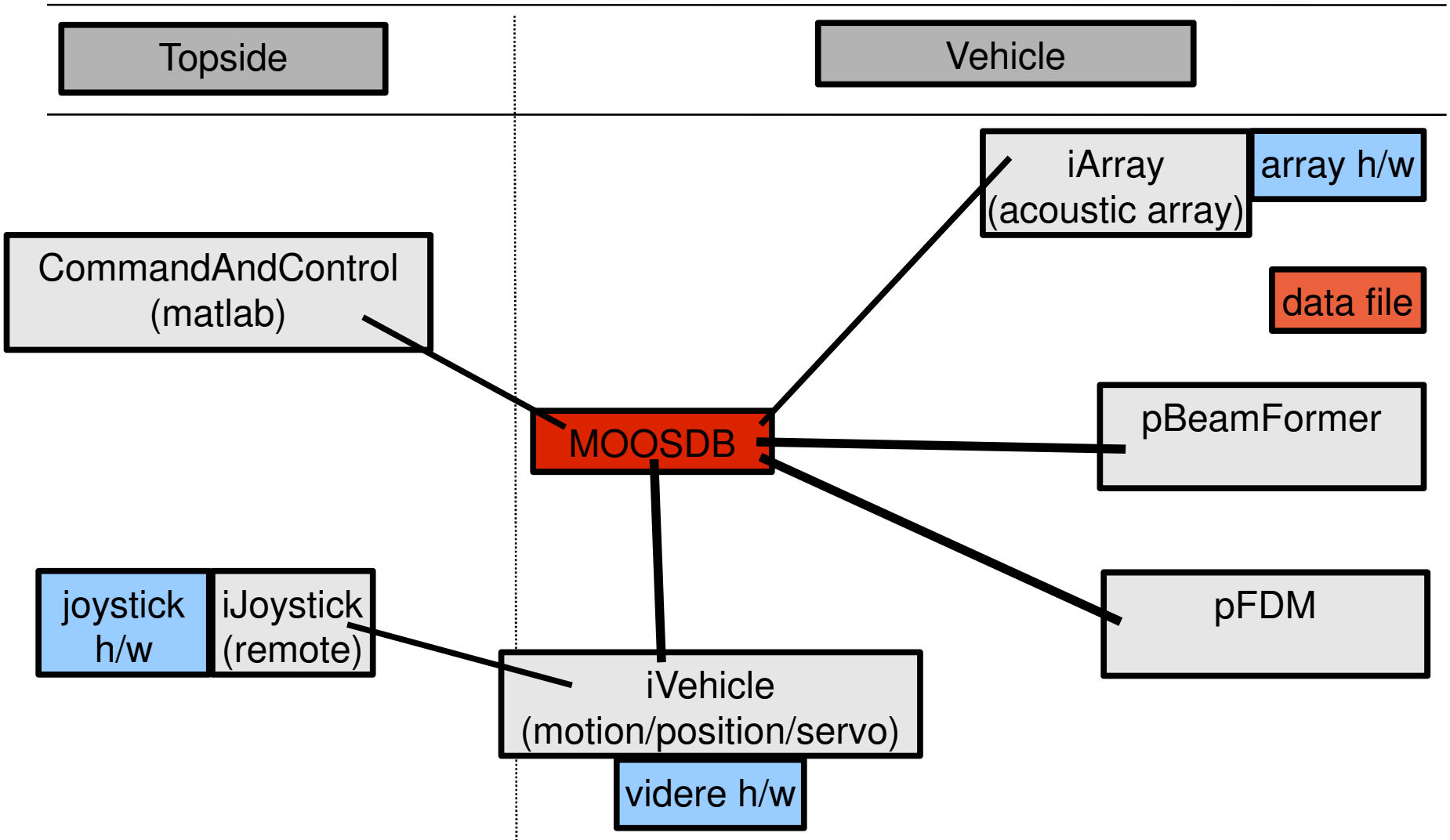




No software framework?

Working theory 1: provide interfaces to the hardware + a software framework

Software Version 1



VEHICLE

CRobot()

- **Videre ERA**
- bidirectional
- thread reads data stream from vehicle and sends external commands to it
- Start(): start/stop the thread (thread trampoline to get around pthread_create()'s C binding)
- Get(): nav, sonar.
- Set(): actuators.
- Send(): commands
- SetDeadZone(): zero axes if too small

iVehicle.cpp

- OnStartUp();
  - instantiate CMoosVehicle
    - cRobot* m_Vehicle
  - Start()
- OnConnectToServer();
  - register to QUIT msg
  - register to COMMAND msg
  - SetQuitOnFailedIterate(true);
- OnNewMail();
  - on QUIT, set global flag to false
  - else store COMMAND parameters
- Iterate();
  - if global flag is set, stop/delete Robots and return false
  - else set and send variables for thread

JOYSTICK

CJoystick()

- **Logitech Extreme3D**
- data out only
- <linux/joystick.h>
- thread reads data stream from joystick
- Start/Shutdown(): start/stop the thread (trampoline)
- GetAxes(): return the most recent axes.
- GetButtons: return the most recent buttons.
- SetDeadZone(): zero axes if too small

iJoystick.cpp

- OnStartUp();
  - instantiate CMoosJoystick
    - cJoystick* m_Joystick
  - SetDeadZone()
  - Start()
- OnConnectToServer();
  - register to QUIT msg
  - SetQuitOnFailedIterate(true);
- OnNewMail();
  - on QUIT, set global flag to false
- Iterate();
  - if global flag is set, stop/delete joystick and return false
  - else read, process, post SEVO_COMMAND or SPEED_COMMAND or QUIT

ARRAY

CNistArray()

- **NIST mk3 array**
- 64 channels, 24 bits, UDP socket, 22050 hz
- bidirectional
- unit of data = file
- thread reads data stream from array and sends external commands to it
- Start/Stop(): start/stop the polling thread.
- WriteDataToFile(Filename,NbSamples): write most recent samples to a file

iArray.cpp

- OnStartUp();
  - instantiate CMoosArray
    - CNistArray* m_Array;
  - Start()
- OnConnectToServer();
  - register for QUIT msg
  - register for SEND_ARRAY_DATA
  - SetQuitOnFailedIterate(true);
- OnNewMail();
  - on QUIT, set global flag to false
  - on SEND_ARRAY_DATA, set flag
- Iterate();
  - if QUITflag is set, stop/delete array and return false
  - if DATA flag is set, write data to file.

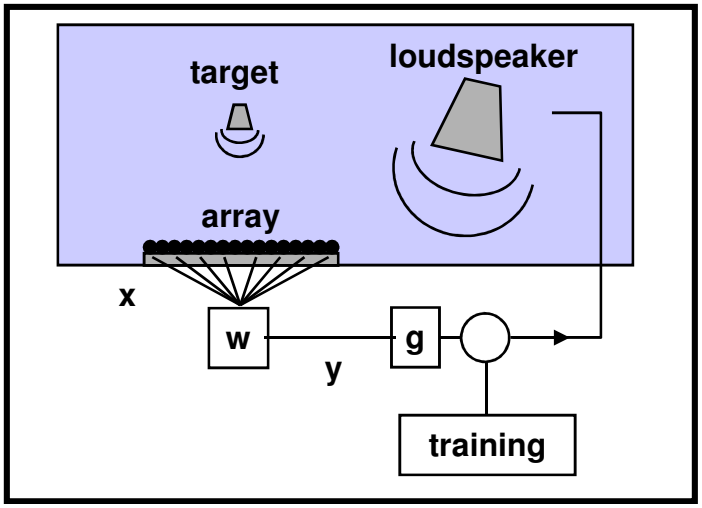
Verdict?

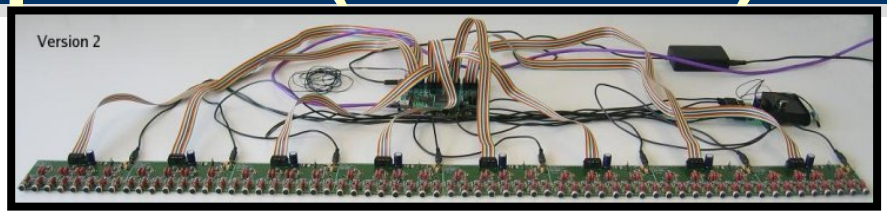
No go: students loved RC-ing the vehicle (so did the ONR sponsor) + the "live" data aspect, but didn't write new code

???

Working theory 2: that was too much hardware to handle at once.

Vurtual microphone (J. Odom)





Distinguishing features:

- higher amplification than a conventional beamformer
- real-time adaptation (MVDR)

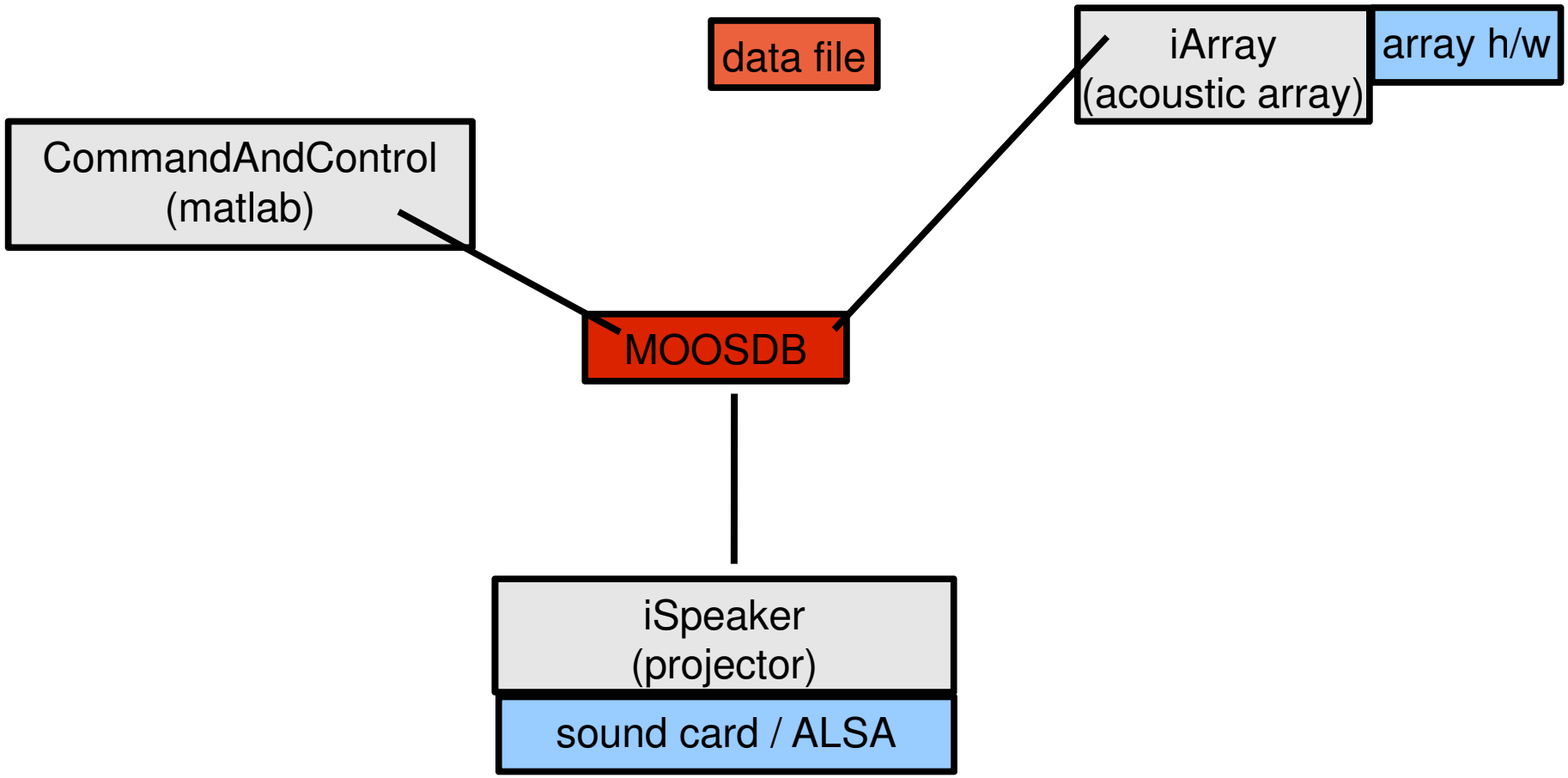
$$y(t_n) = \sum_{\text{microphone m}} w_m * x_m(t_n)$$

$$w_m(t_n) = \sum_{\text{frequency f}} \exp(i2\pi f t_n) \frac{(R^{-1}v)_m}{v^+ R^{-1} v}(f)$$

$$R_{mm'}(f) = H_m(f) H^*_{m'}(f)^+ , H_m(f) = \text{loudspeaker response}$$

$$v_m(f) = \left\{\exp\left(-i(2\pi f d / c)\sin(\theta_{\text{target}})m\right)\right\}$$

Software Version 2



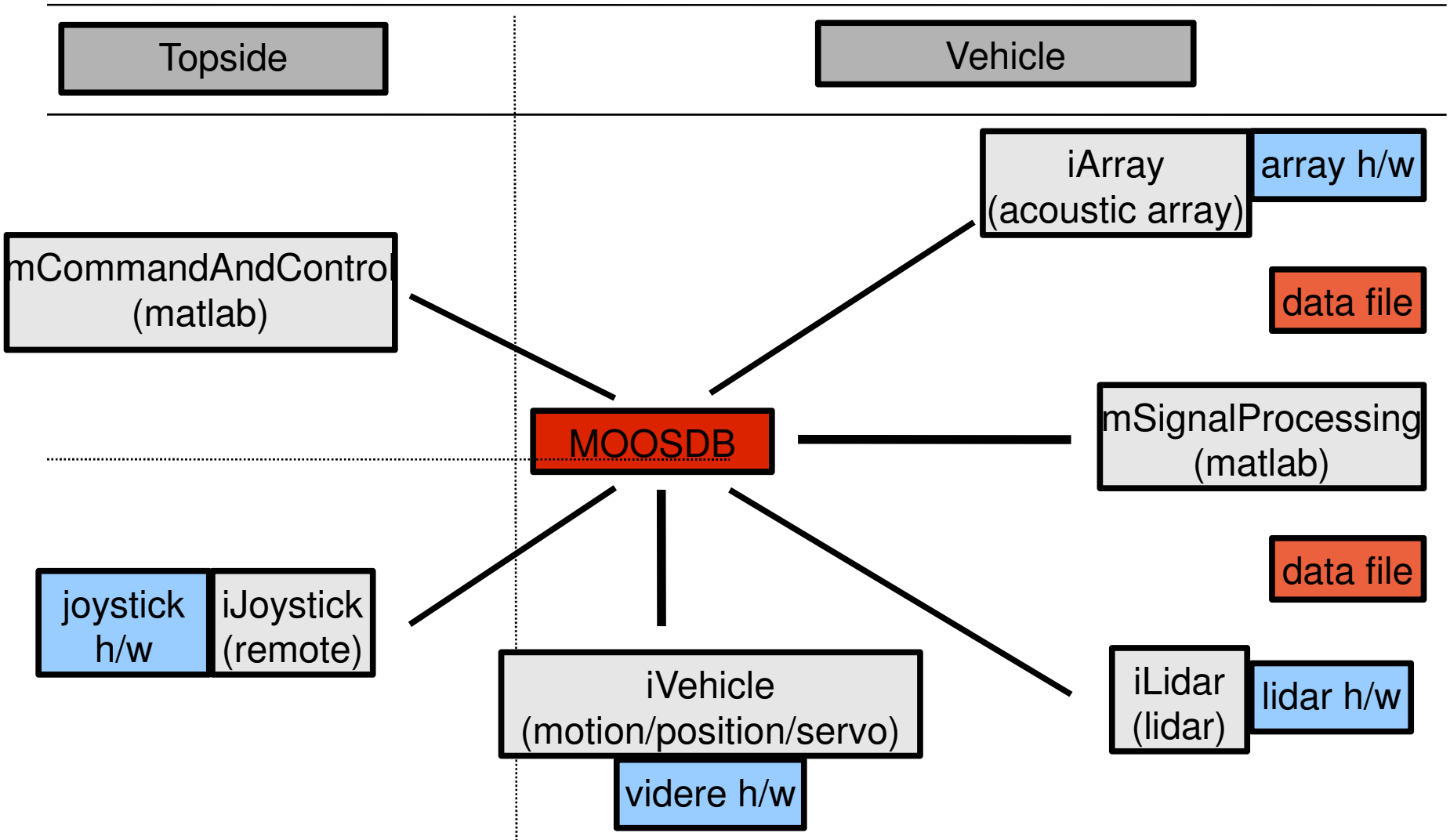
Outcome

- **Worked well - 15dB rejection**
- **Interesting problem:**
  - **mismatch between array clock and sound card clock changed tone frequency**
  - **location of beamformer peak moved a few degrees**
  - **array gain decreased**
- **Q:** why did you use it?
- **A:** because you put Matlab in there
- **in other words, it was not the s/w architecture, it was not too much h/w, it was the presence of Matlab that made it useful!**
- **Test this: multiple projects by separate students with the full hardware suite.**

Was Matlab the enabler?

1. **Matlab/Java is what they teach nowadays.** Not C. Not C++.
2. **In comparison to Matlab, C++ (gsl, blas) is a nightmare to use:**
   - each matrix add/multiply is a function call
   - real/complex support is not always present
   - function names are a mile long
   - each time you change something you need to recompile and redeploy
3. **What if we ran the on-board algorithms directly in Matlab?**

Software Version N



LIDAR

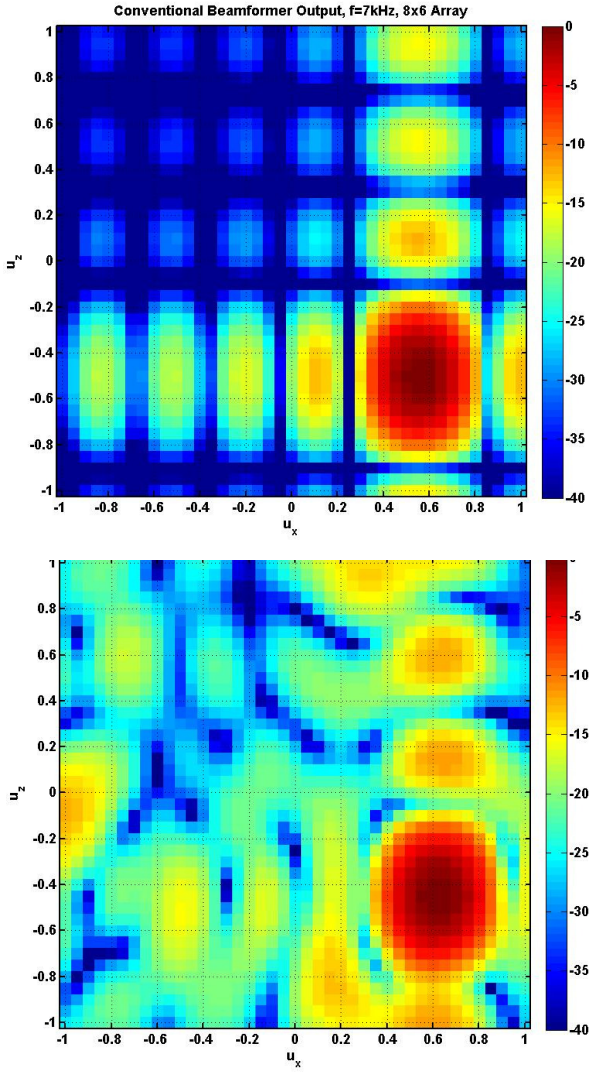
CLidar()

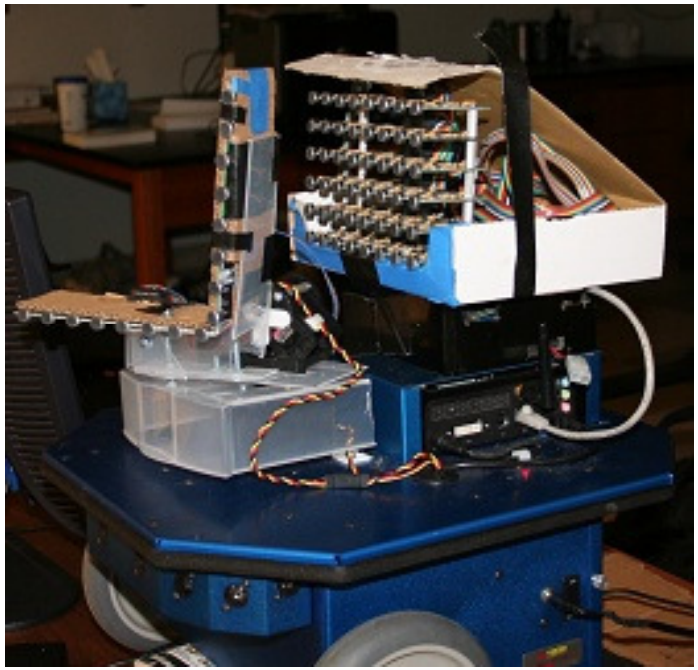
- **Hokuyo URG**
- serial, 5m,10hz, 240° FOV, 0.4 ° res
- bidirectional
- unit of data = file
- thread reads data stream from lidar and sends external commands to it
- Start/Stop(): start/stop the polling thread.
- WriteDataToFile(Filename,NbSamples): write most recent samples to a file

iLidar.cpp

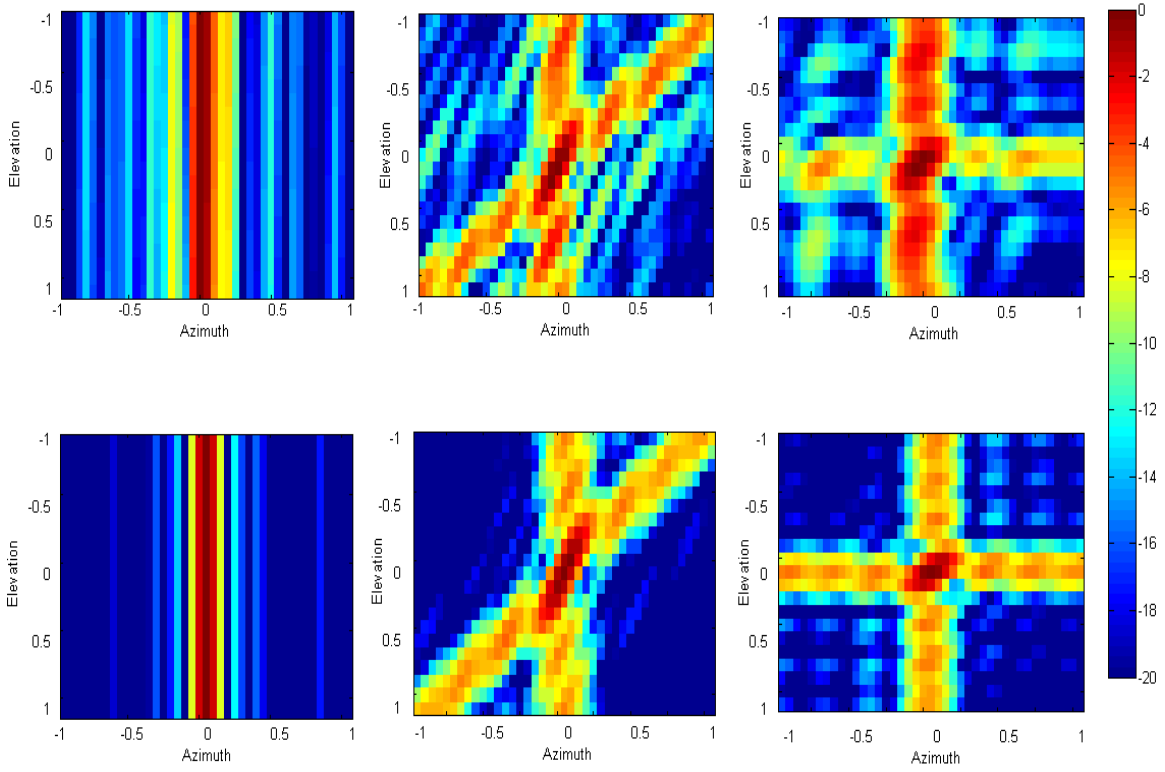
- OnStartUp();
  - instantiate CMoosLidar
    - CNLidar* m_Lidar;
  - Start()
- OnConnectToServer();
  - register for QUIT msg
  - register for SEND_LIDAR_DATA
  - SetQuitOnFailedIterate(true);
- OnNewMail();
  - on QUIT, set global flag to false
  - on SEND_LIDAR_DATA, set flag
- Iterate();
  - if QUIT flag is set, stop/delete lidar and return false
  - if DATA flag is set, write data to file.

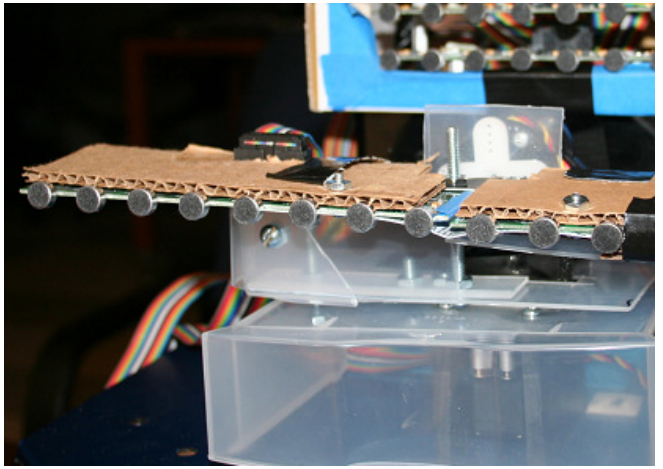
2D beamformer (J. Odom)

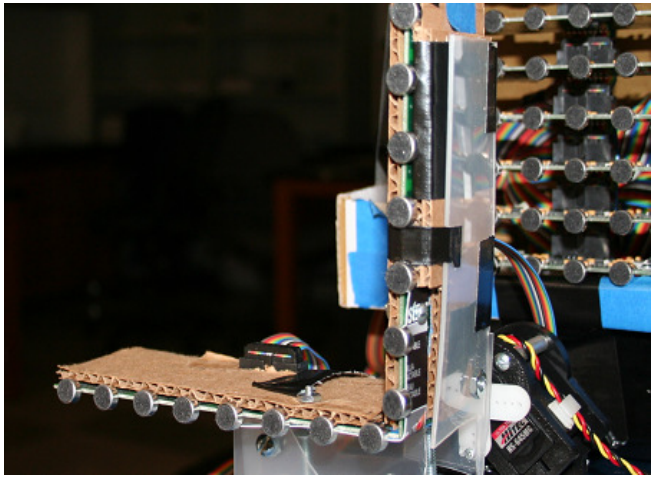




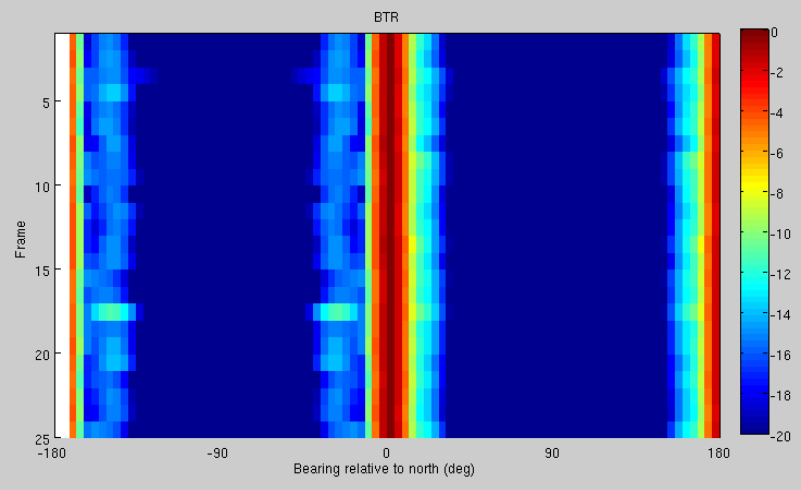
Deformable array (L. Li)

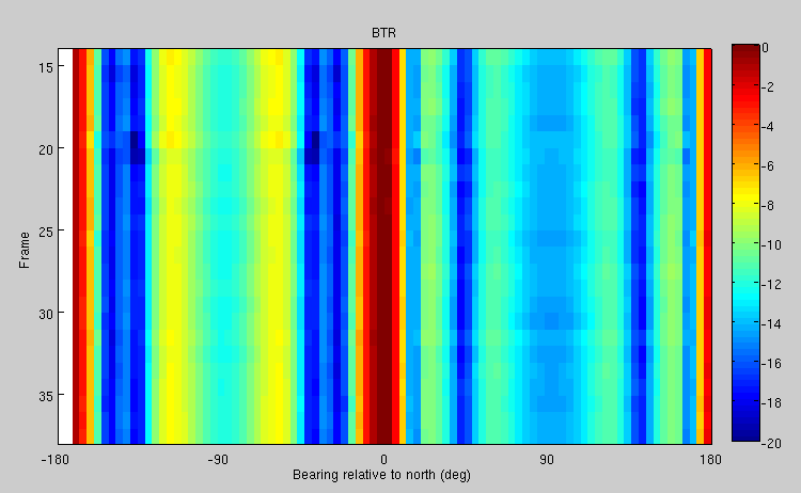


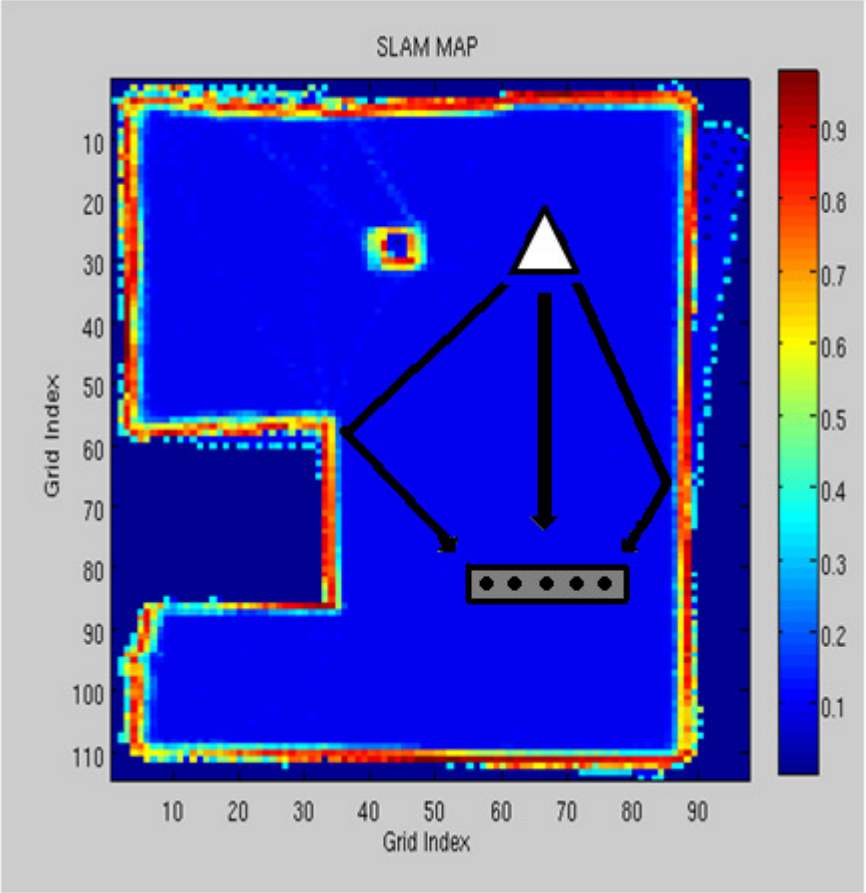




DP-SLAM and Beamforming (C. Potts)







Conclusion

- I'm not advocating running Matlab on-board a UUV but it sure streamlines the integration/testing of signal processing algorithms.
- Would be interesting to look at alternatives that could streamline things - for example Vermeij's pOctaver, or Python's SciPy library with the Python Real-Time Engine.