



McMath-Pierce Adaptive Optics Software

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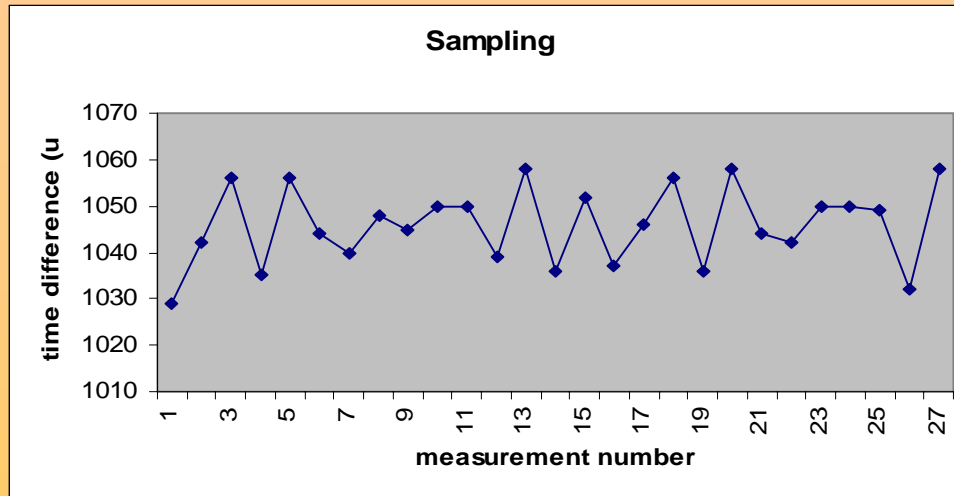
- Linux, RedHat 7.1 on 1-GHz Pentium III industrial PC (8 ISA / 8 PCI)
- Pentium III MMX and SSE instructions provide parallel processing on 4 to 8 pixels for dark and flat corrections and correlation calculation
- Soft realtime scheduling using standard Linux 2.4 kernel
- GCC with inline assembler code for time-critical areas
- Open-source driver for PC-Dig frame grabber

WARNING:

I am a 'nomer, not a software engineer!

Linux or RT-Linux ?

- Regular Linux is good enough if soft-realtime scheduling is used



```
#include <sched.h> /* for sched_setscheduler soft-realtime behavior */  
...  
// variable for soft realtime scheduling  
struct sched_param *p;  
...  
/* set soft real-time scheduling */  
sched_getparam(0,p);  
p->sched_priority = 50;  
if (sched_setscheduler(0,SCHED_FIFO,p))  
    fprintf(stderr,"Could not change scheduler settings\n");
```

Overall Architecture

- Real-time program (ao2) based on test_itifg.c code
- Control program (ctrla2)
- Interprocess communication using 'structure' in shared memory

Main Software Operations

M change AO mode
0 adjust wavefront sensor camera
1 select subapertures
2 pinhole wavefront sensor calibration
3 deformable mirror influence function
4 normal wavefront operation
P change proportional gain of controller
A select axes of wavefront sensing
o open loop (no tracking)
c close loop (tracking)
j jolt mirror and record displacements
m measure and record displacements
C calibration (dark current/flat field)
T acquire new reference image
r read reconstructor matrix file
f flatten mirror
V select live video source, brightness, contrast
q quit

Wavefront Sensor Adjustment

```
root@ira01: /home/keller/tifg/mystuff
255 132 39 0 198 253 187 255 255 255 255 183 217 255 0 156 171 255 0 188
255 255 188 91 211 74 99 144 142 250 198 110 101 141 178 194 245
rms subaperture shifts 0.298889 0.293872
255 132 39 0 198 253 187 255 255 255 255 183 217 255 0 156 171 255 0 188
255 255 188 91 211 74 99 144 142 250 198 110 101 141 178 194 245
rms subaperture shifts 0.298889 0.293872
255 132 39 0 198 253 187 255 255 255 255 183 217 255 0 156 171 255 0 188
255 255 188 91 211 74 99 144 142 250 198 110 101 141 178 194 245
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255 255 188 91 211 74 99 144 142 250 198 110 101 141 178 194 245
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255 255 188 91 211 74 99 144 142 250 198 110 101 141 178 194 245
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255 132 39 0 198 253 187 255 255 255 255 183 217 255 0 156 171 255 0 188
255 255 188 91 211 74 99 144 142 250 198 110 101 141 178 194 245
rms subaperture shifts 0.298889 0.293872
255 132 39 0 198 253 187 255 255 255 255 183 217 255 0 156 171 255 0 188
255 255 188 91 211 74 99 144 142 250 198 110 101 141 178 194 245
rms subaperture shifts 0.298889 0.293872
255 132 39 0 198 253 187 255 255 255 255 183 217 255 0 156 171 255 0 188
255 255 188 91 211 74 99 144 142 250 198 110 101 141 178 194 245
rms subaperture shifts 0.298889 0.293872
255 132 39 0 198 253 187 255 255 255 255 183 217 255 0 156 171 255 0 188
255 255 188 91 211 74 99 144 142 250 198 110 101 141 178 194 245
rms subaperture shifts 0.298889 0.293872
0
```

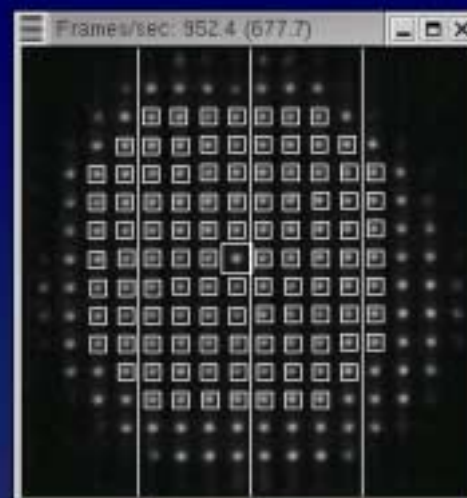
Frames/sec: 952.4 (677.2)

```
root@ira01: /home/keller/tifg/mystuff
>> V
current video source is 0, sources are:
raw data: 0
calibrated data: 1
enter new source: 0
current display brightness is 0, enter new value: 0
current display contrast is 1, enter new value: 2
>> M
current mode is 0, modes are defined as:
adjust wavefront sensor camera: 0
select subapertures: or camera: 1
pinhole wavefront sensor calibration: 2
deformable mirror influence function: 3
normal wavefront operation: 4
enter new mode: 4
>> M
current mode is 4, modes are defined as:
adjust wavefront sensor camera: 0
select subapertures: or camera: 1
pinhole wavefront sensor calibration: 2
deformable mirror influence function: 3
normal wavefront operation: 4
enter new mode: 0
>> []
```

```
root@ira01: /root
keller@ira01 ~]$ xwd > xd0
```


Subaperture Selection

```
root@ira01: /home/keller/lifg/mystuff
rms subaperture shifts 0.298889 0.293872
255 132 39 0 198 253 187 255 255 255 255 183 217 255 0 156 171 255 0 188
255 255 188 91 211 74 99 144 142 250 198 110 101 141 178 194 245
tiltx=0.7272, tilty=0.3520, int=17.3, max= 89, ras=10.2067, minsae=4251
109 subapertures, 109 useful
rms subaperture shifts 0.298889 0.293870
255 132 39 0 198 253 187 255 255 255 255 183 217 255 0 156 171 255 0 188
255 255 188 91 211 74 99 144 142 250 198 110 101 141 178 194 245
tiltx=0.7272, tilty=0.3520, int=17.3, max= 90, ras=10.2067, minsae=4287
109 subapertures, 109 useful
rms subaperture shifts 0.298889 0.293877
255 132 39 0 198 253 187 255 255 255 255 183 217 255 0 156 171 255 0 188
255 255 188 91 211 74 99 144 142 250 198 110 101 141 178 194 245
tiltx=0.7272, tilty=0.3520, int=17.1, max= 89, ras=10.2067, minsae=4273
109 subapertures, 109 useful
rms subaperture shifts 0.298888 0.293878
255 132 39 0 198 253 187 255 255 255 255 183 217 255 0 156 171 255 0 188
255 255 188 91 211 74 99 144 142 250 198 110 101 141 178 194 245
tiltx=0.7272, tilty=0.3520, int=16.8, max= 89, ras=10.2067, minsae=4207
109 subapertures, 109 useful
rms subaperture shifts 0.298888 0.293875
255 132 39 0 198 253 187 255 255 255 255 183 217 255 0 156 171 255 0 188
255 255 188 91 211 74 99 144 142 250 198 110 101 141 178 194 245
0
```

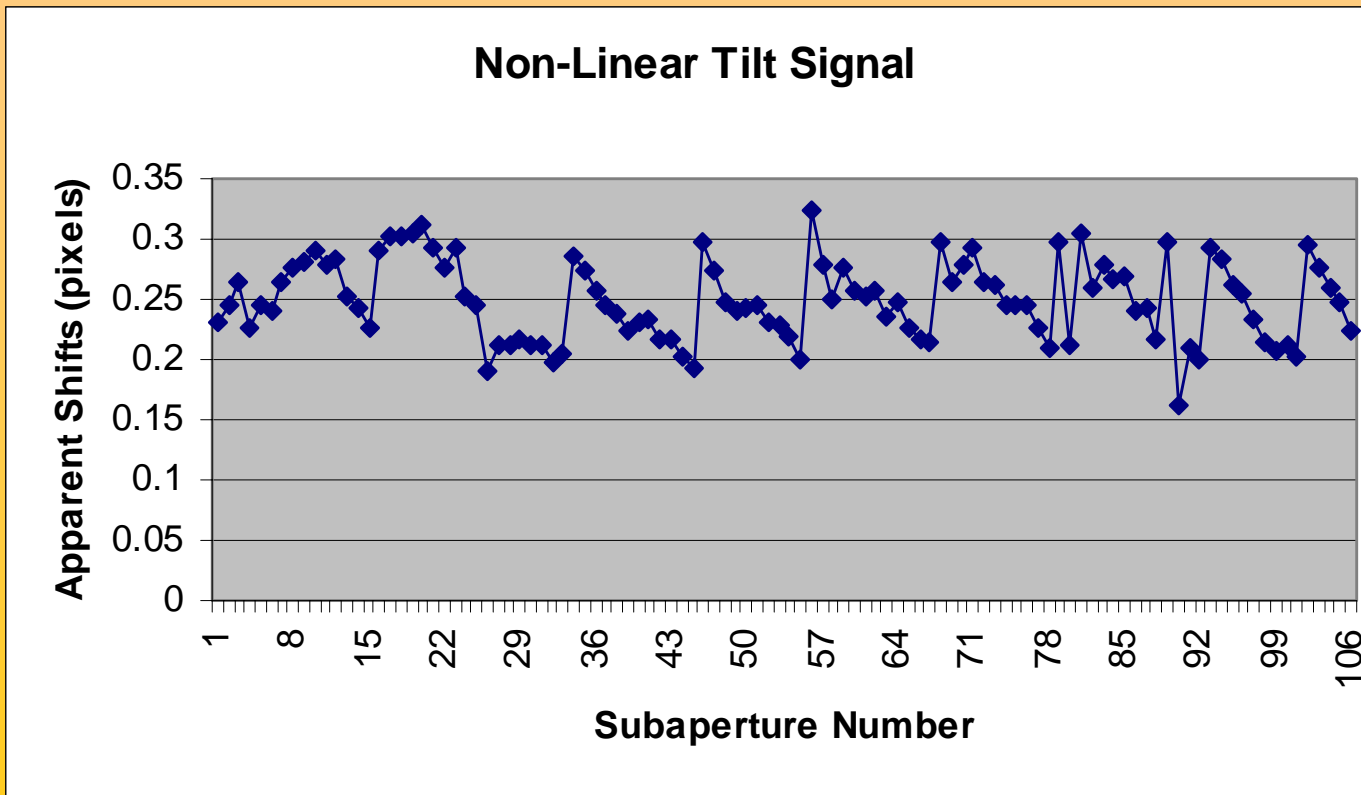


```
root@ira01: /home/keller/lifg/mystuff
current node is 0, modes are defined as:
adjust wavefront sensor camera: 0
select subapertures: or camera: 1
pinhole wavefront sensor calibration: 2
deformable mirror influence function: 3
normal wavefront operation: 4
enter new mode: 4
>> M
current node is 4, modes are defined as:
adjust wavefront sensor camera: 0
select subapertures: or camera: 1
pinhole wavefront sensor calibration: 2
deformable mirror influence function: 3
normal wavefront operation: 4
enter new mode: 0
>> M
current node is 0, modes are defined as:
adjust wavefront sensor camera: 0
select subapertures: or camera: 1
pinhole wavefront sensor calibration: 2
deformable mirror influence function: 3
normal wavefront operation: 4
enter new mode: 4
>> []
```

```
root@ira01: /root
[keller@ira01 ~]$ xwd > xd0
[keller@ira01 ~]$ xwd > xd2
```

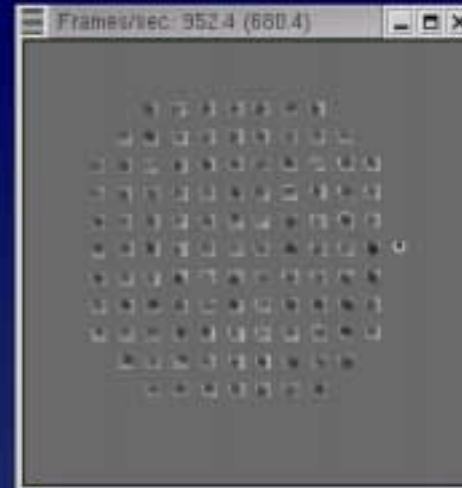
Deformable Mirror Calibration

- Fast switching between two extrema for every actuator
- Determine DM - tip-tilt cross-talk
- Use Singular Value Decomposition to determine reconstruction matrix, can change number of modes
- Wavefront sensor non-linearities: moving tip-tilt to measure works well



Closed-Loop Operation

```
root@ira01: /home/keller/llfg/mystuff
DAC output 2041, 1898
tiltx=0.0554, tilty=0.0429, int=87.9, max=164, rms=24.7854, minsas=206
109 subapertures, 99 useful
rms subaperture shifts 0.844536 0.667725
239 254 0 227 197 251 255 255 228 255 188 148 0 166 0 0 17 8 255 180
209 255 154 0 255 0 187 136 0 203 255 180 178 180 180 180 180
1.179 0.170 0.963 -0.867 0.657 -0.670 -2.172 -0.691 0.968 -0.987 0.141 0.497 0.3
50 -0.793 0.341 0.398 0.046 0.063 -1.299 -0.270 -0.084 -0.193 -0.037 1.191 -0.84
1 1.063 -0.339 1.437 0.067 -1.090 -0.209 0.219 0.415 0.373 0.162 -0.078 -0.383
rms focus 0.083398, DM focus 184.098657
DM-TT correction terms 60.065121 -23.504251
DAC output 2065, 1895
tiltx=0.0668, tilty=0.0337, int=86.9, max=169, rms=24.7854, minsas=138
109 subapertures, 107 useful
rms subaperture shifts 0.783492 0.653822
253 254 0 227 192 251 255 255 228 255 192 137 0 166 0 0 22 0 255 180
209 255 154 0 255 0 187 121 0 203 255 180 178 180 180 180 180
-1.936 0.183 0.754 -1.553 -0.168 0.735 -0.698 1.148 -1.645 1.288 0.521 0.590 0.9
58 1.195 2.131 0.660 -0.869 0.358 1.826 0.328 -0.749 -2.337 -0.282 0.716 -1.576
1.516 -0.863 0.939 0.616 -1.779 -0.360 -0.093 -0.260 -0.153 0.236 0.749 0.951
rms focus 0.044312, DM focus 184.009782
DM-TT correction terms 63.552662 -22.557823
DAC output 1937, 1858
[]
```



```
root@ira01: /home/keller/llfg/mystuff
pinhole wavefront sensor calibration: 2
deformable mirror influence function: 3
normal wavefront operation: 4
enter new mode: 4
>>V
current video source is 0, sources are:
raw data: 0
calibrated data: 1
enter new source: 1
current display brightness is 0, enter new value: 80
current display contrast is 2, enter new value: 3
>>V
current video source is 1, sources are:
raw data: 0
calibrated data: 1
enter new source: 1
current display brightness is 80, enter new value: 50
current display contrast is 3, enter new value: 3
>>f
>>T
new reference image acquired, saving it to file
reference image saved in file so_ref.dat
>>c
>>[]
```

```
root@ira01: /root
[keller@ira01 ~]$ xwd > xd0
[keller@ira01 ~]$ xwd > xd2
[keller@ira01 ~]$ xwd > xd6
```

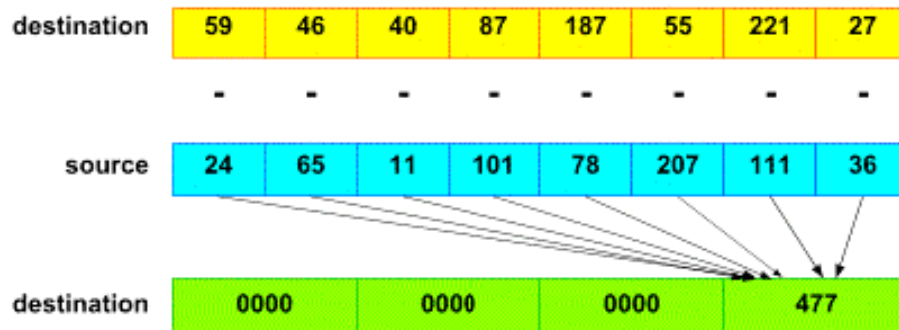
Programming Environment

- Gcc with inline assembler
- Trivial access to ISA cards (digital-analog converters)
- Itifg device driver for PC-DIG frame grabber
- Pentium III MMX (parallel integer operations on 64 bits) and SSE instructions (parallel floating point operations on 128 bits)
- Profiling with gprof, gcov, PMC

Code Snippet

```
movq    (%1), %%mm1
psadbw (%2), %%mm1
movq    8(%1), %%mm0
psadbw 8(%2), %%mm0
paddw  %%mm0, %%mm1
movq   16(%1), %%mm0
psadbw 16(%2), %%mm0
```

- `movq` instruction moves 8 pixels simultaneously into MMX register
- `psadbw`: sum of absolute differences of 8 pixels with 8 pixels of reference, every 2.5 clock cycles
- But Pentium III can only load 1 byte per clock cycle (on average)
- Performance is limited by 1GByte/s I/O limit, not by processing power!
- 256 by 256 pixel correlation tracking at >500 Hz
- wavefront sensing at > 1 kHz with 200 8 by 8 pixel subapertures



Profiling 1

- Profiling with gprof
- Measures execution time of subroutines

```
% cumulative self self total
time seconds seconds calls ns/call ns/call name
42.83 28.79 28.79 117059 245944.35 390230.57 shtracker
25.13 45.68 16.89 400927075 42.13 42.13 sae
22.18 60.59 14.91 main
9.37 66.89 6.30 114020 55253.46 55253.46 shvec2actvol
0.40 67.16 0.27 Sigio_Catcher
0.09 67.22 0.06 117 512820.51 512820.51 Display_Image
0.00 67.22 0.00 1 0.00 0.00 Init_Devs
0.00 67.22 0.00 1 0.00 0.00 Parse_Args
0.00 67.22 0.00 1 0.00 0.00 Setup_Bufs
0.00 67.22 0.00 1 0.00 0.00 Startup_X11
0.00 67.22 0.00 1 0.00 0.00 makedarkgain
```

Profiling 2

- Profiling with gcov
- Counts how often a line of code is executed

```
1232601      switch (axes) {
1232601      case AO_AXES_XY:
7395606          for (ix=-NO;ix<=NO;ix++) {
36978030      for (iy=-NO;iy<=NO;iy++) {
30815025          d = sae(ix,iy,sn);
30815025          diff[ix+NO][iy+NO] = d*d; // <<<--- squaring now !!!
30815025          if (cmin>d) {
1232601              cmin = d;
30815025          }
30815025      }
6163005      }
1232601      break;
```

Profiling 3

- Profiling with Performance Monitor Counters
- Uses hardware counters in Pentium processor
- Measures a large variety of processor events

Event			Events	Events/sec
0x43	67	data_mem_refs	118686424	73317289.63
0x45	69	dcu_lines_in	20469253	12644665.67
0x46	70	dcu_m_lines_in	27167	16726.45
0x47	71	dcu_m_lines_out	40275	24796.92
0x48	72	dcu_miss_outstanding	166551179	102013866.82
0x80	128	ifu_ifetch	1630730503	998834864.72
0x81	129	ifu_ifetch_miss	11451	6863.05
0x85	133	itlb_miss	934	559.78
0x86	134	ifu_mem_stall	199408	123574.28
0x87	135	ild_stall	510	316.05

Real-time Program (ao2.c)

Overall structure in separate window

- Use two vector-matrix multiplications instead of one combined multiplication to see mirror modes
- Add more diagnostic output (mirror modes)
- Add saving of wavefront sensor images
- Include dmtt.gap and svd.c into control program
- Increase display code speed
- Include time/date/AO parameters in measurement files
- Log all commands and output with time/date stamps
- Tip-tilt off-load to telescope
- Complete simulator that runs without instrument
- Improve DM calibration
- Improve WFS calibration