The Environmental Sample Processor: Running an Underwater Laboratory on a Fixed Energy Budget

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Monterey Bay Aquarium
The Monterey Bay Aquarium and MBARI

Monterey Bay Aquarium Research Institute (MBARI)

Not for profit
$45M/yr annual budget
220 people
1/3 Science, 1/3 Engineering, 1/3 Admin
Monterey Bay

Santa Cruz

Moss Landing

Monterey

48 km

26 km

San Francisco
Why Moss Landing?

- Monterey Bay Submarine Canyon within 1-day steam
- Canyon is ~2000 meters deep, comparable to Grand Canyon
- Monterey Canyon Fan is ~3600 meters deep
The Microbial Ocean

71% of the earth's surface
→ is covered with water
(96% of which is in oceans)

Where there is water and light:
→ there are plankton!

Plankton:
+ Produce >50% of our oxygen
+ Form base of ocean's food web
+ Regulate CO$_2$ in our air
- Release greenhouse gases
- Secrete neurotoxins
Harmful Algal Blooms (Red Tides)

- Poison accumulates in shellfish
- Kills fish, birds and mammals
- Closes fisheries and beaches
- Traditional detection takes days
- *Not all Red Tides are Harmful*
Automated Filtering is a surprisingly Old Idea

Continuous Plankton Recorder (CPR)
- First deployed on the R.R.S. Discovery in 1925-27.
- Towed behind ship, prop drives scrolling gauze filter
- Designed to document plankton “patchiness”
- Took ~10 yrs to become “operational”, still in use!
- Mechanically powered
Environmental Sample Processor (ESP)

“Lab-in-a-can”

Positioned 5 – 15m under surface
Battery powered

Development begun 1996
Pucks Replace Scrolling Filter

Function as filter holders and reaction vessels

- Raw water collection
- Sample preservation
- Real-Time Array Imaging

1 inch = 2.54cm
Top & Bottom halves snap together with rubber O-ring seals
ESP Core robotics

- Processing Syringe
- Camera
- Sampling & Collection Syringes
- Top Plate
- Reagent Bags
- Carousel
- Puck Elevator

Top Plate
Deployment Platforms

- ROV tool sled
- Ocean Bottom
- Surface Drifter
- ESP Core
- Pier
Shallow Moored Deployments

- ~15m
- 700kg Total Mass
- Battery
- Bungee
- 20m-50m
- 375kg Railroad Wheel Anchor

Power Management is Key to achieve 6 month deployments
360 Alkaline 'D' Cells

Lead-acid used initially – but only stored 2kWh
+ Alkaline is as energy dense as Li-Ion, but much safer
+ Very inexpensive
- Not rechargable
76kg including waterproof housings
Minimizing “Active” Power Consumption

• Custom Low Power DC Servo Microcontrollers
  – Designed in 2002 – Quiescent draw = ~70mW

• Multi-Master I²C bus
  – Lower power than CAN or RS-485
  – Makes adding controllers easy
  – Eliminates polling

• TI MSP430F169 consumes < 1mW
  – But provides only 2kBytes RAM
  – I²C silicon bugs cost 4 man months

In retrospect...

➔ More kB RAM would have been worth added mWs
Energy Required to actively Process Pucks

• 25 Watt / hrs to process each set of 4 pucks
  - For typical, 3 hour HAB species identification

• Deployment consists of 33 such puck sets

• 25 Watt / hrs / puck set * 33 puck sets = 825 Wh
  - To process all 132 pucks

• Battery has 6000 Wh capacity

• So, we have plenty of energy...

• Right?
Processor load while “Idle” limits deployment

~3 Watt total load while “Idle”
Monitoring Environment
= 75 Wh/day
= 2250 Wh/month
5175 Wh depleted in only 68 days

Far short of 180 day goal :-(

Technologic Systems TS-7200 200Mhz ARM9
64MB RAM, 16MB NOR flash, 2.4 Kernel

Pucks are precious:
Poll environmental sensors for cues to fire off next assay
Reduced Load with custom Linux Host

Finally, in 2014

~500 mW

Radio Modem

Battery Power
10 - 16V

RS-232

LPC3141
PC/104
Host Processor,
~250 mW!

MSP430
Microcontroller

Motherboard
~100 mW

3 x RS-232

I²C

Serial Bus

Servo controllers
(off)

Environmental Sensors

Temperature
Chlorophyll
Salinity

RS-232

Reduced 3W total “idle” load to 1W

~1 Watt total load while “idle”
Monitoring Environment
= 25 Wh/day
= 750 Wh/month
5175 Wh depleted in 205 days!

Mission Accomplished?

Embedded Artists LPC3141 270Mhz ARM9
64MB RAM, 256MB NAND flash, 2.6 Kernel
WHOI Stretch Hose ESP Mooring

- Designed to survive Atlantic Ocean storms
  ESP ~22 meters deep (under waves)

- Wires in stretch hose are >65 meters long
  No twisted pairs – will not pass Ethernet!

- DSL links radio in float with ESP below
  Uses Ethernet within float and ESP

- Idle Mode load increased to >8 W

- Max deployment duration <60 days
  *Even with >3x battery capacity*

- Retrofitting with new 250mW CPU board
  *Does not change much*

WHOI = Woods Hole Oceanographic Institution
High Speed Over Long Wires Saps Power

Symmetric Digital Subscriber Line:
Pushes Mb/s over most any cable
But, links typically use >4 watts

Ethernet:
100BaseT link uses 1 watt
10BaseT uses only 400mW
Old, slow tech saves power!

With today's low power Linux processors, such links blow the power budget
RS-232 cable length vs max speed

RS-232 works well beyond its recommended speed/length limit. MBARI's ESP mooring runs 115 kBaud over 12m cable. Although RS-232 spec would suggest ~19.2kBaud limit.

Much maligned but still used in oceanography:

+ RS-232 is often lowest power option
+ Compatible with every processor
+ No (intrinsic) length limit
  300 baud can push through kms of wire

+ RS-422 can push higher rate on long cables
  - but requires twice as many conductors
SCRIPPS Stretch Hose Mooring

- ESP hangs from 10m stretch hose
- RS-422 used for 65m link to float
- One battery removed to reduce mass
  - Capacity halved to 3000 Wh
- Need 6 month mission duration

2175Wh

 Idle

 Reduced to 3000 Wh

 Battery

2175Wh

Active

825 Wh

3000 Wh

Sorely Missed

➔ Depleted in just 85 days
➔ With 1W load

SCRIPPS = Scripps Institution of Oceanography
Quick Fixes We (briefly) Considered

Suspend-to-RAM?

• Lowers host CPU power by only 100mW
  - Reducing monitoring mode load to 0.85W
  - Increasing deployment by only 15 days

Suspend-to-Disk?

• Concerns about SD card
  - Slow write speed
  - Flash wear over 100s of hibernate cycles
• Hibernation not implemented in 2.6 ARM kernels
Rethinking Requirements

• If all activity is triggered only by time...
  – No need to monitor sensors
  – Host CPU could be powered off
    • Until switched on again by motherboard

• Even this yields only enough power for 140 days
  – Radio has become the power hog
  – If it must shutdown, how will unscheduled access be possible?
Deep sleep while allowing remote wakeup

- Drop the data connection
- Modem functions as a pager.
- Outputs “RING” when it detects an incoming phone call.
- Draw reduced from 500mW to 100mW

Utilizing modem's "low-power standby" mode
Year long deployments possible on 3kWh

- Battery Power: 10 - 16V
- Radio Modem (standby): ~100 mW
- MSP430 Microcontroller: ~100 mW
- Motherboard: ~100 mW
- Wake up system by calling modem's phone # (Waking up system)

Not monitoring sensors while asleep

~200 mW sleeping load
= 5 Wh/day
= 150 Wh/month
2125 Wh depleted in 425 days!
University of Washington's ESP Mooring

- Suitable for open ocean
- Relatively inexpensive
- No stretch hose

40m Cat 5 cable to surface is too long for RS-232

~650kg

Large Float collar protects ESP and Eliminates need for rotating bale

Foam Float Collar (around ESP core)

400 Alkaline 'D' Cells 6.1kWh

Taut Line to 1 ton Anchor
Replace RS-232 with Ethernet?

+ Directly drives 40m Cat 5 cable
+ >100 times faster than RS-232 to modem
+ Unlimited networking potential

- Each device is a computer itself
- Adds minimum of 1W per device
- No “class drivers”
Replace RS-232 with USB?

+ >100 times faster than RS-232 to modem
+ Linux kernel includes many USB class drivers
+ Hubs multiplex 100+ devices per USB channel
+ Directly support additional devices in the float Environmental Sensors, WiFi, etc.

- Adds about 30mW per device
- Hubs draw 150mW each!
- Segment length limited to 5 meters

→ But, we need to span 40 meters.
USB on Cat5 cable

Many Cat5 USB extenders available...
Icron 1850 works reliably over 50 meters of cable:

LEX

Remote Extender
REX

RJ-45
Cat5

Device (Cellular Modem) or USB Hub

RJ-45
Cat5

Host (ESP core)

- Full Speed (12Mb/s) and Low Speed (1.5Mb/s) only
- Supports remote hubs, transparent to software
- 12Mb/s link burns 500mW
- Newer designs support 480Mb/s, burn >2W

- Precludes low power sleep in current ESP design
- Would require a dedicated RING signal from modem

Note: Many other vendors rebrand Icron USB extenders
Most devices ignore requests to suspend
  - Suspended devices still draw ~30 mWs
Most hubs do not support powering down ports
Laptop users simply unplug unused USB devices

→ Embedded systems can do the same

Power USB devices via GPIO controlled switches
  - USB stack sees usual dev disconnect / connect
  - No need to splice high speed data lines
Energy Harvesting

*Need only 50 Wh/day ~= 2W continuous*

- Solar requires least maintenance
- >3 hrs sunlight/day in temperate latitudes
  - Need panel w/peak rating of ~25W
  - 25W panel area ~= 0.25 square meters
- Might blow over existing small surface floats
  - Tipping > 30 degrees interferes with radio
- Rechargeable battery & new float design required
  - But very doable and worth investigating...
The Road to > 6 months on 6 kWh

• High Energy (Alkaline) batteries
• Custom Low Power Electronics
  ‐ Servo controllers optimized for small motors
  ‐ Lower power ARM9 Linux Host
• Avoiding modern high speed serial links
  ‐ Using RS-232 instead of Ethernet and DSL
The Road to > 6 months on 3 kWh

All the previous measures, plus...

• Relaxing requirements for environmental monitoring
  - Allowing complete shutdown of Linux host

• Radio comms power management
  - Exploit modem's low-power standby mode

In Future:

• Indefinite Environmental Monitoring...
  - with solar panels on the surface float!
Acknowledgements