LazerBlazer

V0.3

Requirements, Outline Design & Proof of Concept

17 Aug 2003

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1 Introduction

1.1 Intended Audience

This is for ChrisM as a record of the design work so far, for ANO as the basis for further development work, and for anyone else who might be interested!

1.2 Background

The current BatBlaster is extremely successful, being used in competitions worldwide by thousands of skiers. It is simple in concept, fits a range of boats, doesn't require expensive equipment on a per-skier basis and most importantly has proven itself in the field.

It does, however, have a number of limitations:

- The "measured" point is to the end of the line not the skiers ski.
- There is not allowance for the bowing of the tow line due to windage.
- There can be some degree of "sticking" at of the end of each arc.

The intent of the current development is to produce an equally reliably product, which resolves the above issues, at not significantly higher cost (preferably less), and with equal (or greater) reliability.

2 Requirements

2.1 Description of challenge

2.1.1 Course

- Entry gate on center line of course.
- 6 bouys, in two rows, 11.5m either side of the centerline.
- Exit gate back on the center line.
- Total course length 250m.

2.1.2 Progression

- Boat speed 49kph – 58kph steps.
- Rope length starting 18.25m reducing to 9.75m in steps.

2.2 Equivalent measurements

2.2.1 Range - Angular

Allowing for ~1.5m from arm to ski, we can calculate the half-scan angle as

arcsin(11.5/13) => 62deg

To be safe, and to allow for any mis-alignment of the measurement head, we should probably allow a half angle of 70deg, 140deg total.

2.2.2 Resolution - Angular

A resolution of ~30cm is required at the edge of the scan.

For short ropes (11.5m) this equates to

arcsin(11.8/13) – arcsin(11.5/13) => ~2.5deg.

For longer ropes (20m) this equates to

arcsin(11.8/20) – arcsin(11.5/20) => ~1.5deg.

2.2.3 Resolution - Time

Based on observations of swing rates, position updates in the region of 10Hz to 20Hz should be sufficient to ensure accurate ongoing measurement of position. At the ends of the scan it might in theory be possible to go down to 5Hz, but it is safer to stick with the higher rates.

2.3 Other factors

2.3.1 Boat

Rough observations suggest the boat may change in pitch by between 10-15deg according to speed.

The top of the pylon is probably between 1m – 1.5m above the water surface.

2.3.2 Ski visibility

The ski itself is clearly visible for about 2m each side of the centerline. Similarly, for the edge 3-4m, the ski is also visible. In between the wake obscures the ski to varying degrees.

2.3.3 EMI

The pylon and battery feeds can be expected to couple a fair degree of interference form the engine ignition systems.

3 Outline system

3.1 Rejected Options

Given the required resolution it is hard to form a system based on RF unless you use the high microwave region. This would push up cost and development difficulty.

GPS isn't an option due to limited update rates for non-military receivers and insufficient accuracy unless one uses the most advanced measurement techniques.

Direct computer based vision analysis is potentially a very attractive solution. To help locate the end of the ski you would probably want to use a retro-reflecting band round the skiers ankle. You'd then probably want to illuminate with a strong IR source and use an IR filter in front of the camera. You'd also probably need a hood on the lens to limit the vertical range of the camera to a thin band. The major issues are cost of the computing hardware (the camera itself can probably be had quite cheaply), and whether the system could successfully deal with confusing reflections from the water surface. Polaroid might help to reduce the issue with surface reflections, but due to the cost issues this solution is not being pursued.

3.2 Proposed solution

The proposed solution is to have a transmitter on the boat which outputs short, high-power IR pulses at ~128kHz, 3/16 duty cycle (SIR IRDA encoding).

The pulses are generated using a narrow beam-angle IR LED, mounted to point vertically downward, collimated into an ~2deg divergent beam using a lens, scanned using a front silvered mirror mounted at 45deg in a beam cube mounted on a small motor mounted and finally spread in the vertical domain to an ~15deg beam in a shallow cone at 5degree to the horizontal using a cylindrical fresnel lens mounted blow centerline on the exit port of the beam cube.

The optical head is powered for only 180deg of the scan, and then only every other revolution. Coupled with the short pulse length this limits the thermal rise of the LED and allows maximum transmit power. The selected rotation rate is 28.125Hz (115.2kHz / 2^12), and this gives an update rate of ~14Hz.

The skier has a bracelet round their ankle with 5 wide angle, integrated IRDA receivers mounted in a 180deg arc. These sensors are cheap and hardy devices including amplifiers, daylight filter, ambient light and compensator. They are mounted inside a "U" shaped Perspex pipe (along with buffer circuitry) and attached to an ankle strap.

In the final system the buffered signal will be fed to a small box with a stub antenna out of the top. Both the skier and boat station have these RF Transceiver modules, capable of 160KHz with a code balanced to within 10%. To simplify system design, all data uses Manchester coding giving ~80kbps channel.

The skier station starts in receive mode and does nothing until it receives an activation code with its unique code from the boat station (this allow multiple skiers to have leg units using the same frequency range). The boat station switches to rx mode after each attempt at contacting the ski station and once it receives a response goes into active mode.

In active mode the boat and ski units swap from tx to rx and back at 14Hz. 5ms before the scan is going to start, the boat station sends a start code to the ski station and switches to rx mode. The ski station switches to tx mode and after ~5ms of 101010 preamble, transmits ten 0s and then couples the output to the IR detectors, sending:

- 0 if no IR pulses are detected by any of the ski receivers during the preceding 1/64000s bit-period.
- 1 if one of more IR pulses are detected during the preceding bit period..

At the end of the active scan period (17ms after the start) the ski station transmits ten 1s, then its station ID and finally swaps back to Rx.

During the scan the boat station listens for 1 pulses. The largest group is identified and the ceter is taken as the moment the center of the beam passes over the skier. By counting cycles since the start of scan it is then possible to work out the angle.

The station ID at the end of the scan is a good check to make sure no accidentally cross-associations have occurred. Once the boat station goes back to Tx it can then transmit position info back to the ski station, which could be used to drive audio signals to an ear piece for the skier.

At the end of the run, the boat station sends a stop code to the ski station, inactivating it and leaving it listening for more activations.

Auxiliary system elements include a UI at the boat station, careful timing (probably synchronizing the microprocessor clock to the clock used for the optical Tx head), careful motor speed and phase control (including a sync pulse tied to the mirror), klaxon to indicate bouy passing, carefully filtered overall power supplies and careful attention to water

4 Optical budget

4.1.1 Introduction

The key factor associating whether the design can work is the optical power budget.

- The BIM2 RF modules from RadioMetrix are well proven, are fairly cheap and have the features required.
- The micro-controller software will need testing, but it really ought to be possible to get the code working.
- Waterproofing of the skier module is hard, but with careful design should be fine (mount the sensors inside a transparent pipe, attached to a bayonet sealed into the side of an IP68 box and plug at the other end).
- Reflections need to be considered, but are unlikely to give a stable / bright enough source to be confused with the main beam.

The optical power budget is however more of an issue.

- Economic hi-power IRDA devices are limited in their maximum output.
- We need to consider the safe / legal exposure limits in case of someone looking into the beam.
- The beam width has to be wide enough to give a reasonable number of pulses per scan.
- The beam height has to be high enough to allow for the pitch of the boat to change.
- Allowance needs to be made for losses at all the optical surfaces, particularly the ski station housing with surface water.
- Allowance need to be made for the power reduction experienced by high power LEDs after prolonged use.

4.2 Detailed analysis

To get the horizontal resolution, beam width needs to be around 2deg (narrower will be hard to arrange optically and even 1deg may be hard). At a scan rate of 28Hz & pulse rate of 115.2KHz, this gives

(115200*2)/(360*28) => 20 pulses per scan

The easiest way to allow for boat pitch is to have a 15deg vertical beam angle. Smaller angles could be used if there was some kind of adjustment of Tx head angle was available (say automatic by mounting on a damped pendulum or just manually), but lets use 15deg for worst case analysis.

At maximum rope length of 18.5m (20m including arm length), the beam area (ignoring beam shape) is approx

20*20*sin(15)*sin(2) => 3.6m2

Using a Sharp IS1U20 integrated detector with a 60deg acceptance angle, the required receive power is around

0.04/(0.7) => 60mW/m2

Using the OD-50L IR LED (Opto Diode Corp) with a (3/16)*(1/4) duty cycle and a reasonable heatsink, the data tables indicate a maximum pulse current of about 5A, giving about 400mW emitted power. Given the narrow inherent beam angle it isn’t too hard to couple almost all of this power into the output beam, especially if the collimator lens is set to image the output lens of the LED.

Spread over the 3.6m2 beam area the 400mW output gives a receive power of ~110mW/m2, i.e. above the minimum by a factor of ~1.85

This is a factor of 1.8 up on the calculated minimum, but doesn’t include any losses for the optical elements, spray, mounting tube, etc.

Typical losses assuming uncoated optics and an Al coated mirror might be roughly as follows:

• Uncoated collimating lens	85%
• First surface Al mirror at ~900nm	85%
• Fresnel lens for vertical spread	90%
• Perspex housing	90%

This gives a total tranmission fraction of ~60% prior to taking into account water losses, which gives a Tx/Rx ratio of ~1.1

This ratio will be boosted by the fact that the beam is actually elliptical (so of less area at the target), but will obviously be impacted by spray, water on the receiver housing and the power drop-off towards the edge of the beam.

In all likelihood the above power budget will be okay at the shorter rope length but insufficient at the longest lengths.

Way of improving the situation include the following.

- Reducing the power target by reducing the beam vertical size. (Makes alignment harder)
- Reducing the power target by reducing the horizontal size. (2 deg is already optically challenging, but 1deg might be possible.)
- Reduce the duty cycle to allow the pulse current to be increased. (This is possible if we add code to reduce to say only generate alternate pulses when we’re trying to lock onto the skier and then change to full rate but only for 90deg centered on their predicted position. This would allow us to go upto the maximum pulse power of 10A, giving a beam power of ~600mW and power boost of x1.5).
- Consider specialized optics to make the beam power more uniform and improve the edge performance.

- Use an diode laser rather than an LED. (More powerful, but much more expensive and harder to drive safely.)

At this stage improving the duty cycle seems the best approach, but isn't required in the initial prototype system as its effect is fairly easy to model (an increase in maximum length of 22%)

5 “Proof of concept” system

5.1 Introduction

The only way to validate the preceding analysis is to build a real system. Given that the area of greatest concern relates to the optical power budget, that’s what needs to be explored in most detail and secondary elements such as the radio link and software can be replaced by alternatives (in this case direct wires and an oscilloscope!) for initial testing.

5.2 Implemention Details

5.2.1 Light source

The selected light source is a OD-50L IR LED (Opto Diode Corp), as this is the highest power generally available IR LED. It has an ~8degree included beam angle and can survive pulses upto 10A. Power output is a linear 100mW/A up to 1A, but then becomes gently non-linear with 400mW at 5A and 600mw at 10A.

The major limiting factor to the use of the higher currents is the thermal impedance of the die to case interface. This limits <u>average</u> power to ~1W when a good heatsink is used.

To a first approximation, instantaneous power is given by:

$$P = I*1.6 + I*I*0.38$$

where 1.6 is the junction voltage drop, and 0.38 is the effective resistance.

This equates to the following maximum duty cycles.

0.5A	Indefinite operation
1A	50% duty cycle
5A	5.8% duty cycle
10A	1.8% duty cycle

The 3/16 IRDA encoding scheme was designed for a relatively low duty cycle of 19%, and coupled with a 180% scan on alternate revolutions we get down to ~5%. This allows use of 5A pulses with no further intelligence.

(As noted in the optical power budget section, for the final system this will most likely need to be changed to a more advanced scheme with 1.5% duty cycle to allow use of 10A pulses.)

5.2.2 Light Driver – Optical head

Given the large currents and short pulses, the inductance / loop area of the drive circuit needs to be kept very small. As a result the drive proper is mounted on a small circuit board directly attached to the LED, and is very simple in nature.

It starts with a low ESR tantalum capacitor, value 100uF, 10V Kermet CZZZ. This provides all the power for the short active pulses while maintaining the voltage with only a small drop. As a result of this capacitor the current supply from the control unit is a steady low value and can be relatively high inductance.

Connected across the capacitor is a series circuit of:

Resistor->LED (with parallel reverse connected diode) -> FET switch

The resistor is 0.1R and its prime purpose is to decrease the variation in LED current with supply voltage. This helps achieve even power during a burst, but more importantly minimizes the impact of LED characteristics with batch variation and temperature.

The reverse connected diode is to clamp any transients at the end of the pulses, and in the prototype is a XXXX.

The FET switch obviously turns on and off the supply current. It needs good high-speed performance, coupled with a low on resistance and ideally logic level gate drive. The component selected for the prototype a IRFXXX.

The FET gate is pulled to ground with a 10K resistor (to ensure the FET is off when the line is undriven) and also has a 33R/100pF AC termination to correctly terminate the drive signal.

There are test points across the current limiting resistor and on the ground to allow monitoring of the pulse currents (100mV/A), and adjustment of the supply.

5.2.3 Light Driver – Control unit

In the control unit there are two main sections relating to the light source:

- Power supply
- Pulse generator

The power supply in the prototype is a current limiter followed by an adjustable voltage source, described in detail in the Power Supply section.

At the heart of the pulse generator is a standard IRDA encoder/decoder. The encoder f*16 clock input is driven at 1.8432MHz off the first tap from a divider chain attached to the main system crystal running at 3.6864MHz. These frequencies give a final output pulse rate of 115.2kbps, which is the maximum “slow form” IRDA encoding rate. As will be described later, the same timing chain provides timing to all of the other system element, and in due course the 3.6464MHz clock will provide a phase coherent clock to the system microcontroller.

The Tx enable signal is driven by the combination of four control signals.

- Motor speed lock achieved signal
- An ~28Hz clock derived from the main system clock but generated using a secondary divider chain, with the hi-low transition synchronized to a pulse indicating the transmit head being positioned for scan start.

- An ~14Hz clock which results from dividing the above clock by 2
- An ~14Hz clock which is independent of the system clock and generated using a tertiary divider chain which is clocked of the scan start pulses.

Pulses are transmitted when the signals are Hi, Lo, Lo, Lo.

The combination of these signals means that no pulse except when:

- the motor is up to speed
- the beam is the 180 degree scan window
- the beam is only energized alternate scans.

Later developments may make the control circuitry a little more complex to give the duty cycle required for 10A pulses.

5.2.4 Position Encoder

To allow speed control and sensing of the scan start position, the beam cube has an encoder disc on top. It has two circles, the inner one with a single white line and the outer with 32 lines. Mounted on the upper fixed surface is a pair of narrow-beam reflective encoders (SY410). These generate an ~28Hz sync pulse and a 900Hz speed control pulse.

5.2.5 Motor Speed Control

The motor unit selected is the scanning assembly from an HP LaserJet II printer. It is a high quality brushless motor + driver, will run from a 9V supply and has a 5V-0V torque control signal (5V = stationary, 0V= ~500Hz with the original mirror assembly).

A 900Hz signal is generated from the main system clock using the main divider chain, and used as the reference input to the TypeII comparator in a ‘7076 PLL. The signal input is the 900Hz pulse from the optical encoder.

The output of the phase comparator goes through a second order loop filter, with an additional capacitive lead element to compensate for the large inertia of the beam cube. This is buffered and applied to the mid point of a divider chain to reduce the control voltage range to max out at about 50Hz. (This limits the possibility for a runaway condition leading to serious damage.)

The current filter is mainly based on experimentation and has slower step response than is ideal. After a sharp angular rotation of the entire assembly there is a 1-2 cycle 200deg oscillation at about 2Hz. The filter will need to be revised based on detailed analysis and simulation in the final system, but is fine for now.

The 7046 has a lock output, which after filtering is used to feed one half of a dual monostable with a 0.5s delay. This currently feeds the pulse enable circuit to stop pulse generation unless the motor is locked. Longer term the suppression of pulses on unlock after the motor is up to speed will be retired and replaced by software compensation for the disturbance.

The monostable output is also used to drive a bi-colout led on the control panel. Red of unlock, green for lock.

5.2.6 Receiver

The receiver is made of five IS1U20 integrated IRDA receivers mounted on a plastic strip at 45deg intervals. As each detector has a 60deg acceptance angle this gives full coverage of the forward 180deg plus a good degree of vertical spread.

Each detector has a 0.1uF ceramic chip capacitor directly on its power leads, which are connected in parallel to a 220uF tantalum capacitor to provide a reliable power source despite long cable lengths. The 5 output signals and integrated and buffered using an SMT 74ACT08 quad AND gate wired to form a 5 I/P AND gate. To provide shielding the plastic strip is backed with a bit of brass shim connected to the cable shield.

The whole assembly is mounted inside a 13mm O/D, 10mm I/D Perspex tube bend into a horseshoe. One end is sealed to the cable using adhesive lined heat-shrink tubing. The other end is blocked off using a melted and glue filled bit of Perspex pipe, seal to the main horseshoe using the same heat-shrink.

The inner diameter of the horseshoe is chosen to suit the average ankle size just above a ski boot. Due to the nature of the bones in the leg it tends to stay pointing forward rather than turn. It is fix to the leg using a lightly stretchy cat collar with a snap buckle for quick attachment (not shown in the photos).

In the prototype system the wire is connected to a snap socket to protect the test skier from getting tangled.

5.2.7 Receiver Output & Indicator

The 28Hz scan signal + receiver output are currently buffered and sent to two BNC sockets on the top of the control unit for connection to a ‘scope. To give a quick indication of whether a signal is being received, the detector signal is used as the trigger pulse for a 100ms monostable. The output of this is used to drive a bicolour led, red for no signal, green for signal detected.

5.2.8 Power supply

The power supply is quite simple.

The incoming lead goes several times round a ferrite core, then enters the control box. It is fused and switches then goes to the PSU board. The PSU board starts with a transorb voltage dependant surge device which clamps the voltage at no more than 16V. The feed then goes through a dual wound choke/capacitor filter before finally reaching a 2200uF 16V filter capacitor.

From there the 5V and 9V feeds for the logic and motor are derived using normal fixed regulators, with the case being used as the heatsink. A green led is connected across the 5V supply to give a “power on” indicator

The light drive PSU is slightly more complex. The current limiter is implemented using a 3-terminal regulator (type XXXX) and is currently set at 1.25A (equating to a 1R 2W resistor connected between the Adj and Out terminals). This is primarily a safety feature, providing enough current to maintain the capacitor voltage during a normal scan, but preventing continuous 5A or 10A drive is there was a problem with the pulse control circuitry.

The voltage regulator follows the current limiter and by controlling the voltage on the drive capacitor controls the pulse current. This is again implemented with a standard 3-terminal regulator (type XXXX) but with a XK variable resistor connected between Out, Adj and ground.The adjustable current limited supply for the light driver is as described earlier in this document.

Final output from the unit is via a 6-way connector, set up to provide maximum isolation between supplies. This means that the return path for the three main supplies (LED, Motor, Logic) are kept separated but parallel right back to the regulators. This limits cross-coupling due to voltage rise in the ground leads.

5.2.9 Mechnicals

The system mechanicals are fairly simple, but care has to be given to maintaining alignment along the main optical axis. Aluminium was used through out for ease of machining.

The trickiest element is the beam cube which needs to be finely balanced to allow it to run at speed. This was done by attaching appropriate lengths of 2.8mm tungsten welding rods (selected for maximum density) in positions calculated using a finite element analysis of both static and dynamic balance. The beam cube is attached to the motor via a reamed hole in the bottom of the cube using the original beryllium copper wave washer and a new circlip.

The mirror and front lens are attached to the beam cube using a non-corrosive silicone glue to give some flexibility while not attacking the Al coating on the front of the mirror.

Attachment to the pylon is via a modified BatBlaster Mk4, with adjustment to the boat planning angle being via washers under the relevant three point attachments.

The LED is bonded into an Al assembly using thermally conductive epoxy, which in turn is bonded to a heatsink.

5.2.10 Opticals

The LED is mounted at the top of a lens tube made from a hair mousse can which happened to be the right size (much cheaper than buying the minimum length of commercial pipe).

Approximately 100mm lower down is a d=50mm, f=100mm glass lens obtained from a cheap “paired lens” magnifier. This images the LED output lens and captures almost all the optical power (the edge of the beam is only about 35mm dia at this point). The resulting beam has a 2deg divergence (beam divergence is set by the angle the source subtends at the lens).

The narrow beam continues down and enters the top of the beam cube through a 39mm aperture.

Inside the beam cube is a 45deg front silvered 38mm x 51mm mirror. Ideally the silvering would be Au as this has 98%+ reflectance at NIR wavelengths, but the prototype is Al as it is easier to obtain in small quantities.

The reflected beam exits via the front port which has a f=150mm cylindrical acrylic fresnel lens. The length of the lens tube below the collimation mirror is adjusted so that the fresnel lens images the collimation lens. The resulting beam is spread to ~15deg in the vertical domain.

The centerline of the fresnel lens is displaced below the center of the exit window so that the beam is displaced downwards to form a cone with an angle of ~5deg to the horizontal. This ensures the beam centerline intersects with the receiver centerline all the way round the scan.

5.2.11 Misc

The control to transmitter connection is run over a SVGA monitor cable as this is fully shielded and has three or four 75R coax cables for the motor control, LED drive and speed sync signals.

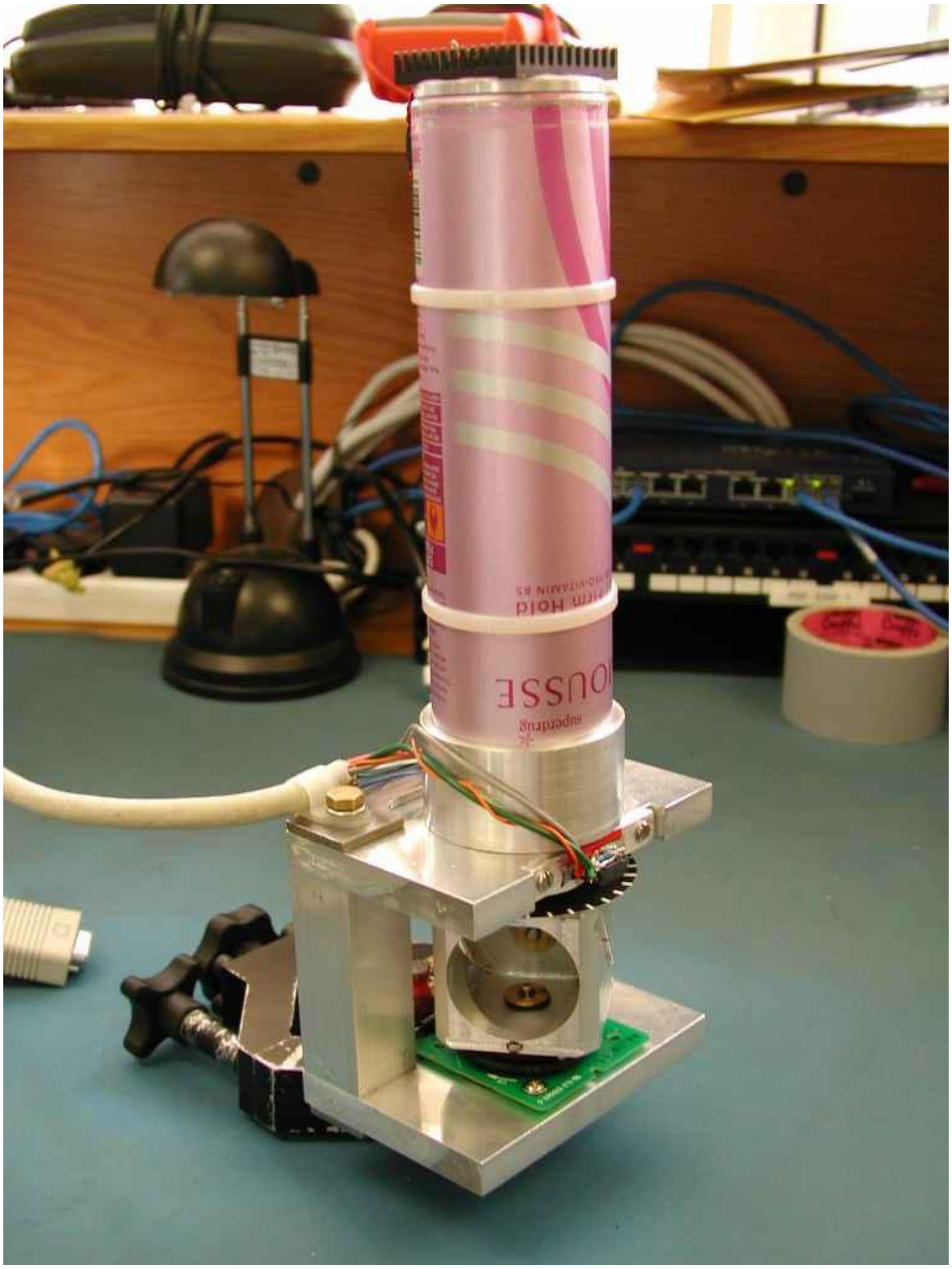
The control case is a die-cast Al box for the RF screening properties.

The prototype is powered of a standalone lead-acid battery, but the final version will have an internal battery pack and be able to take power from the boat 12V feed.

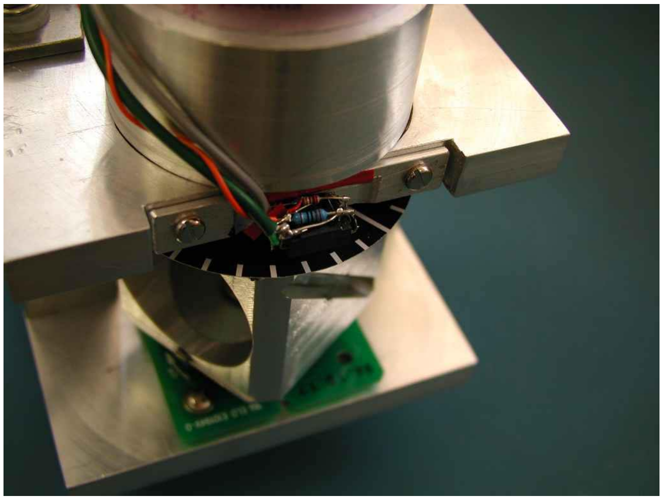
All logic signals which need to run long distances are buffered with ACT logic and AC terminated at the far end.

5.3 Pictures of the test system

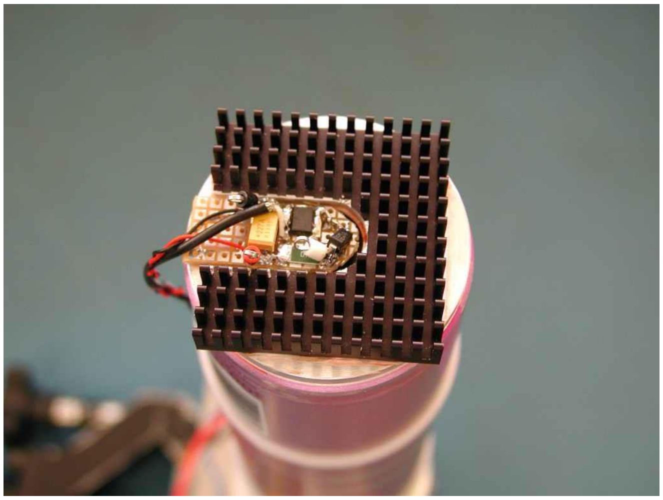
5.3.1 Transmitter



Transmitter head including mounting bracket

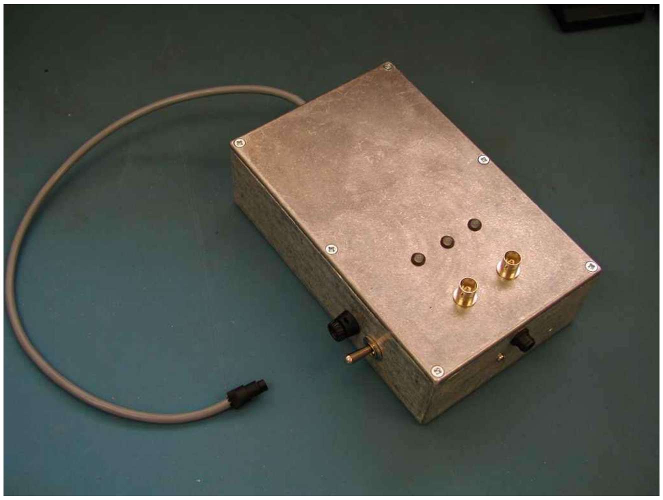


Close-up of encoder, beamcube and motor



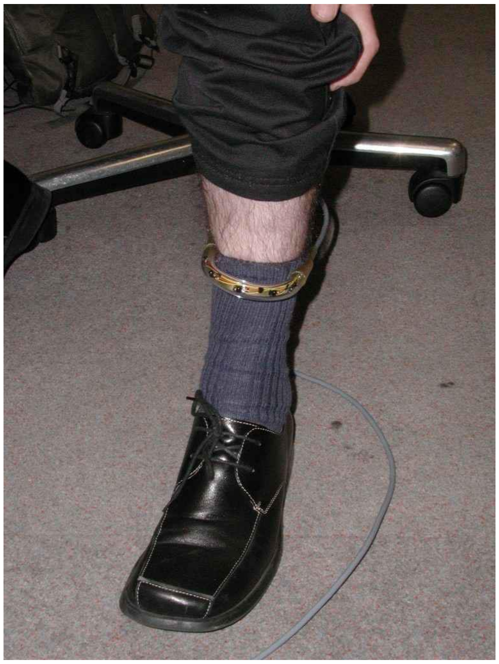
LED driver & heatsink

5.3.2 Controller



5.3.3 Receiver

Receiver electronics in case with seals



Receiver modeled on Mr Batty's leg!

6 System Performance

Initial tests on dry land show good, stable detection of pulses, and it is easy to read the “skier angle” off the ‘scope display.

In terms of distance, pulse are reliably received up to the full 23m of the test wire, though at the limit of this range the usable vertical size of the beam is only ~2m. This is inline with the power budget analysis.

Making some estimates on water / spray losses it is expected that in the water we’ll reliably get between 16m-18m, with the gap being easily closeable by the duty cycle / power boost described earlier.

These live trial are only pending arrangement of a suitable test day.

Change History

Version Information	Description of Change	Section(s) Affected
Version 0.1 Colin Dancer June 2003	Initial Draft	All
Version 0.2 Colin Dancer Aug 16 2003	Update to include prototype info	All
Version 0.3 Colin Dancer Aug 17 2003	More detailed information added on the prototype	All