4B25 Coursework 5 : William Eustace (we229@cam.ac.uk), Emmanuel College

A prototype system is developed to measure mechanical strain in yacht hulls concurrently with motion of the hull, with a view to detecting delamination in bonded matrices and sandwich structures, or weakening of other structural components, before it leads to failure. The system logs data to a microSD card for easy retrieval and scrutiny; work has started towards a custom printed circuit board with integrated power supply regulation.

0.1 Problem Statement & Stakeholders

Historically, small boat design has featured significantly over-built structures. The advent of mass-produced yachts produced with the aid of CAD/CAM has resulted in a dramatic reduction in weight and wasted material, but at the cost of very occasional structural failure [1]when inadequate monitoring of the structure has been performed. Structural failure on yachts often stems from previously sustained damage or fatigue, and in both cases a change in load paths is common; the capacity of the secondary load path is then exceeded by a normal operational loading and failure occurs. However, this secondary load path will be associated with a larger deflection; if this can be measured under excitation of wave loadings on the structure, and that wave loading normalised, the damage may be detected before failure occurs. Significant stakeholders are mass production yacht builders, who may be interested in incorporating structural monitoring to their designs in order to provide added reassurance to end users; yacht owners who make long passages during which hull damage could be sustained (for example by collision with a floating object or by stress of heavy weather); and commercial yacht operators, who cannot rely on their customers reporting damage to their vessels.

0.2 State of the Art

The recommended approach to detecting structural damage is to lift the yacht out of the water after any possibly damaging grounding and have it professionally surveyed. However, surveyors cannot detect this damage easily or with complete reliability due to clamping by keel bolts [1]. Routine monitoring is suggested, including by surveyors themselves [2], but this is not necessarily practical. Fibre-optic strain gauges are routinely installed in very high performance and very large yachts [3], both to compliment non-destructive testing for failure avoidance and to confirm model predictions for structural design purposes. Large ships have for many years been fitted with “hull response monitoring systems”, typically featuring measurements of strain, motion, and often other metrics (for example engine thrust).[4] A search found little similar technology targeted at small and medium sized ($< 70'$) yachts.

0.3 Approach

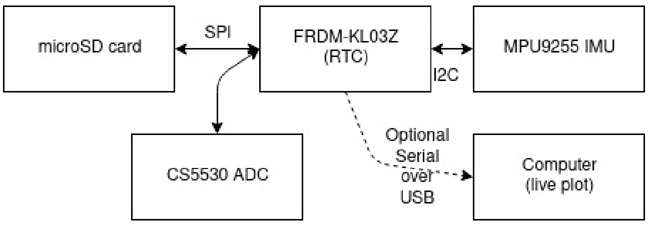


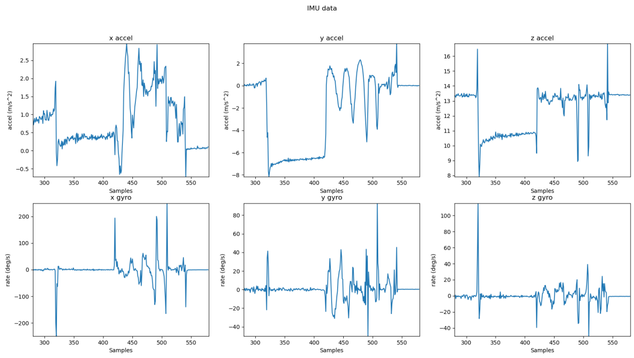
Figure 1: Block diagram of prototype system

Hull strain is measured with a single 350Ω resistive strain gauge in a Wheatstone bridge, connected to a 24-bit ADC with sensitive differential amplifier, configured for a gain of 64x. Inertial measurement data (“6 axis”, i.e. gyroscope and accelerometer) is obtained from a commodity MEMS device (in the prototype an Invensense MPU-9255). Data are logged to a microSD card, which may be connected to a computer for retrieval of data. In the planned printed circuit board embodiment, parts will be different: an STM32F411 will be the new microcontroller, the extra RAM allowing for much lower power operation by bunching writes to the microSD card; also, a Bosch BMX055 will be used instead of the MPU9255, as the latter part is now obsolete (though the author had many of them lying around from past projects!) and its replacement does not support 3.3V operation, desired for the other components. Data processing on board was not attempted, since no sea trial data have yet been gathered; it was felt more productive to gather the raw data and experiment with algorithms *post hoc*.

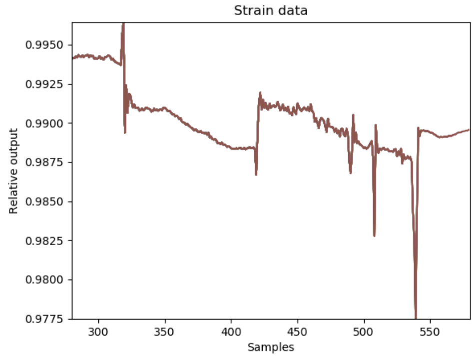
1.1 Power

Power draw is not a key concern aboard the typical cruising yacht; an example run by Cambridge University Yacht Club has around 350Ah of usable battery capacity (assuming discharge to 50%) at 12V, charged under engine use at around $1.2\mathrm{kW}$. This vessel is equipped with a chart-plotter, always left on during navigation for safety reasons, that draws approximately $60\mathrm{W}$; the power draw of this project is expected to vanish in the noise. However, it is interesting to characterise the power consumption of the prototype. Much of this comes from the strain gauge(s), which are expected to draw around $14.3\mathrm{mA}$ at $5\mathrm{V}$ (with 350 Ohm strain gauges and reference resistors). Two traces were captured; figure 2a is perhaps more interesting, as it shows the power draw during an SD card write in some detail. The first spike is likely during power-up; the second two spikes are powering of the on-card charge pumps for flash erasure, as first the target sector and then the file system are erased and written. Although this looks dramatic, with a peak current (for the whole system) of $110\mathrm{mA} = 550\mathrm{mW}$, the average power (from figure 2b) is only around $200\mathrm{mW}$. Further power reductions would be easily achieved by putting the SD card in sleep (or de-powering it entirely) when it is not in use and by bunching writes to reduce power-up time. Provision for both of these have been made in the design for the first PCB version. Note that the measurement frequency was adjusted somewhat after these measurements were taken, which will have some influence on the measured power.

1.2 Measurements



(a) IMU data

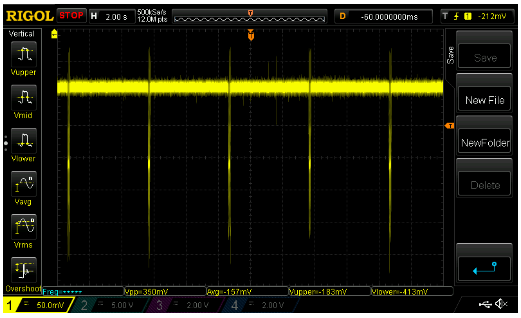


(b) Strain gauge data.

Figure 3: Measurements from prototype while being waved about (‘mechanically excited’); sample rate 10Hz. The droop from 320-420 samples represents the piece of MDF used relaxing after being put down, superposed on a downward trend discussed in the text. Offsets had not been calibrated in this example.

Some sample traces were plotted while the prototype was mechanically excited. Figure 3 spans approximately 30 seconds, during which time (in particular when the object is at rest from 320-420 samples), a downward trend in the readings can be observed. Readings were rarely consistently static, usually had these slow trends superposed upon them even when at rest. This is attributed to poor surface adhesion (the gauge was glued, for test purposes, to a piece of MDF using cyanoacrylate glue, rather than epoxy, so creep is quite likely); poor power supply regulation (the PCB will use a high precision linear regulator and lots of filtering to try and reduce this); and thermal effects. Fortunately, the creep has frequency content mostly below 0.1Hz, whereas the signal expected from yacht motion is mostly from 0.1Hz to 3-4Hz, so most data are likely retrievable by filtering. As minimal hardware low pass filtering was installed in this prototype, it is also possible that part of the creep here is aliased mains pickup or other spurious input, though the data converter contains an inbuilt notch filter for mains harmonics. Practical use of the project should use a fully-active Wheatstone bridge, with adhered strain gauges in the first and fourth quadrants (to maximise sensitivity) and non-adhered (floating) strain gauges in other positions to cancel out thermal effects. The strain gauges used here were very low cost (circa £0.20 each), so this is easily achievable.

(a) An SD Card write



(b) A longer average (with SD card writes visible).

Figure 2: Measurements of voltage drop across a 3.9Ω 1% resistor on the 5V supply rail of the device (with microcontroller and all sensors powered from this rail).

2.1 Project Progress Report

Due to pressure of project work, the printed circuit board anticipated was not designed in time for fabrication in 2019. Since it could not score credit in this module, it has been put on hold until time allows the continuation of the monitoring project. Nonetheless, a plausible prototype has been assembled using breadboard: the interfaces with the CS5530 and IMU (a legacy device used for the prototype only because it was to hand and therefore free) and the SD card have been proved viable. Remaining tasks are: improve strain sensitivity; reduce measurement noise in strain; resolve PCB; run FAT rather than custom light file system on SD card (for ease of data transfer).

References

[1] Report 8/2015, Marine Accident Investigation Board, 2015. `https://assets.publishing.service.gov.uk/media/55408664e5274a157200005b/MAIBInvReport_8_2015.pdf`, accessed 2019-11-15.

[2] “Hull Construction, Keel Securing and what to look out for”. Presentation to RYA YM Instructors 2019 conference. Author withheld as information is commercially sensitive.

[3] Marine Applications. Epsilon Optics. `https://www.epsilonoptics.com/marine.html`. Retrieved 2019-12-25.

[4] SSC-401: State of the Art in Hull Response Monitoring Systems. Ship Structure Committee, 1997. `http://www.shipstructure.org/pdf/401.pdf`. Retrieved 2019-12-25.