Simultaneous Measurement of Pressure, Temperature, and Conductivity with Counters

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Abstract - **Modular sensors of pressure, temperature, and conductivity with frequency outputs can be simultaneously sampled with counters. Power for the counters is inconsequential and there is no serious limit for counting period. Many sensors can be sampled simultaneously by simply adding counters. This is an old technique but complex sensing packages with low power, modular, frequency output sensors make it an attractive one. The number of stages of the counter, the stability of the sample interval, and the clocking of the serial shift register that moves the count to the logger are important considerations. Sample clock instabilities or timing errors must be detected and corrected and lost high order bits due to overscaling of the counters must be restored. With these considerations, modular frequency output sensors can be added to an underwater system for an incremental cost of one electrical penetration per sensor.**

I. INTRODUCTION

The simplest interface a digital sensor can have with a controller is a frequency output. Although it is possible for a twisted pair or even a single conductor with seawater ground return to communicate the signal frequency, a three conductor cable containing a power lead, signal lead, and a common ground, is the system that is generally used. Frequency is the ultimate scalar because its reference, time, is available both accurately and independently in every controller and data logger. Any single sensor is easily monitored by either counting output cycles for a fixed time interval or by measuring the period of a fixed count of cycles.

Period measurements require a dedicated precise and high frequency clock for each sensor. (The frequency of the measuring clock times the sampling duration is the resolution of the signal frequency. In practice, this is the number of cycles measured times the measurement clock frequency divided by the frequency of the signal. This points out the need for a high frequency clock for precise period measurements.)

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If many sensors are to be logged, simultaneous period measurements can be costly in power and complexity. Counting cycles, by contrast, is an inexpensive process. Precision in counters is proportional to the number of cycles counted. Simply extending the period during which the signal is counted increases the precision. This is independent of the number of stages in the counter. If sampling bandwidth is a concern, adding a phase-locked-loop (PPL) frequency multiplier may be required [1]. Even with a PPL, adding sensors with frequency outputs to a system requires little incremental cost in power and complexity. Little more than a buffer amplifier [2], ripple counter [3], and serial shift register [4] per sensor is needed. A latch and PPL may be advised in some circumstances.

II. CIRCUIT CONSIDERATIONS

The counter that measures frequency output is simple, but has pitfalls that must be avoided in order to obtain accurate data. Fundamentally, the frequency to be counted must have well defined transition times. After buffering, it must have digital levels compatible with the counter. Capacitively coupling the signal to an inverting gate, biased with a high value of feedback resistor which puts it into a region of linear gain, is sufficient for most signals [5]. If further sharpening is needed, a second buffer amplifier (for example, a second inverting gate) can be used. In the case of an extra noisy signal, an inverter with hysteresis (a Schmitt trigger [6]), may be needed. (A single stage of amplification, by inverting gate buffer, is satisfactory for signals from about a tenth of the digital level of the counter to several times the digital level.) Figure 1 shows a typical buffer for four signals with clamping diodes to keep the CMOS gates off when the sensors are not powered, and thus not producing signals. When the diodes are held positive (CMOS gates "on"), the feedback resistors bias the inverters to their linear gain operating points and small signals coupled through the capacitors are amplified.

The counter is typically a ripple counter so that the propagation delay time, the time it takes for a clock transition at the input to affect the last stage of the counter, must be less than the strobe time for the parallel to serial conversion to occur in the shift register. While this conversion is occurring, new clock transitions of the sensor signal must be saved. There must be no propagating ripple in the counter. A single stage latch is sufficient to save cycles of the sensor signal during this strobe for modest frequencies, but a first-in first-out (FIFO) latch [7] might be needed to avoid missed signal transitions in an extreme case. The ripple counter must propagate the last clock passed by the latch, to the last counter stage, in a single cycle of the frequency to be counted. This requires a fast ripple counter if the number of counter stages is great.

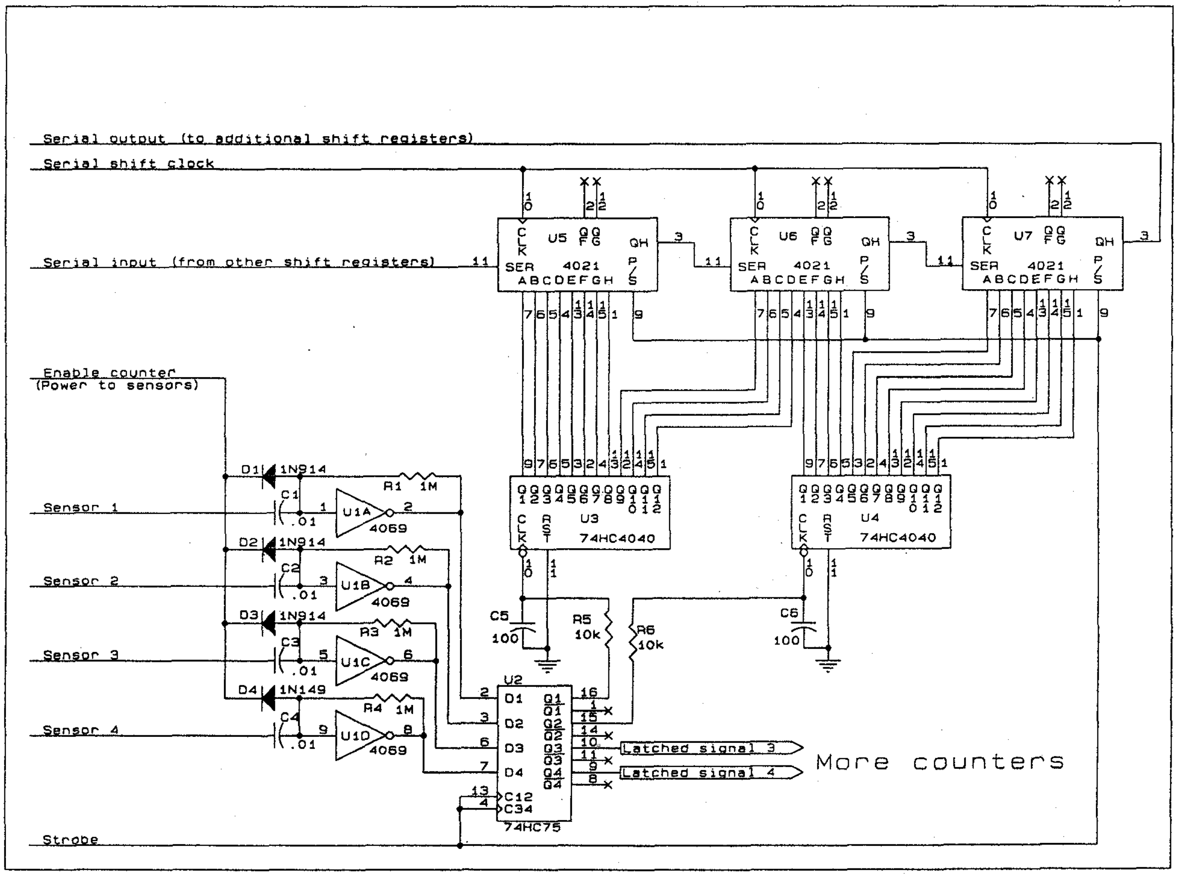

Fig. 1. Inverting gates buffer frequency signals from four sensors to a quad latch which permits a strobe of 1 microsecond duration to hold up signal transitions for frequencies up to 1 MHz. The strobe latches the ripple counter outputs into the shift register if the setup time for the shift register is substantially less than 1 microsecond. Propagation time through high speed CMOS counters is short enough to avoid error in readout. The sensitivity of HC devices to short commutation pulses requires an RC filter on the clock input to the counter to avoid false triggers.

III. COUNTING VERSUS ALTERNATIVES

There are three conditions where counting may be preferable to period measurement for sampling frequency. Counting is the most economical system when using many sensors at once, when frequency resolution vs. time resolution is either not critical or a PLL multiplier can be used to increase resolution, or when simplicity and low power are critical to instrumentation. Period measurements work well when only one sensor is being used, but cannot be used with multiple sensors without great replication of hardware.

When both frequency and bandwidth are important, a PLL with a frequency divider in the feedback path can provide the required resolution at short sample intervals. This frequency multiplication is accounted for during data processing. Wave measurements on the continental shelf bottom with a Digiquartz$_{TM}$ (Paros Scientific) pressure sensor have such a requirement and the nominal 30 kHz frequency is multiplied by 32 before being sampled at 4 Hz from the counter. The Matlab$_{TM}$ (The Math Works) code to is multiplied by 32 before being sampled at 4 Hz from the counter. The Matlab$_{TM}$ (The Math Works) code to reconstruct the pressure must divide the incremental counts by eight to obtain frequency.

```
%Convert the signal from Paros
%s/n 55374,0-270 meter depth.
%P=C(1-(To/T)^2)(1-D(1-(To/T)^2))
[Values of C,D,and T previously
entered]
P=8000000./P;%1/4 sec*32
P=(To./P).^2;
P=1-P;
P=C.*P.*(1-D.*(P));
P=P./1.45038-10;% convert to dbar
```

IV. WORD LENGTH AND OVERSCALING

Since the count will eventually exceed the range of the ripple counter, overscaling is unavoidable. The records found in the data logging device need to be processed before they can even begin to be understood. As the recording of the counter is cumulative (it does not set itself back to zero every time it takes a measurement), output values must be differenced before any algorithm may be performed. Even after this difference function is performed, there still may seem to be wild values which misrepresent the data.

Some of these wild points may be the result of the overscaling that occurs when one sample has the counter full and the next sample has the counter empty. Another explanation of strange values may be that a counter has rolled over more than once, as is characteristic of a short counter. Both of these problems can be resolved with a simple repeating algorithm which adds back overscalings until the result is plausible. Determining if the correct number of overscalings that have occurred depends on knowledge of the physical environment being measured.

Procedures to restore lost overscalings and to edit other irregularities may be written in Basic, Fortran, Matlab, or any other data processing program that permits repeated calculations. The following code was written in Matlab to decode data from a pressure sensor. This code restores the occasional overscaling of the 24 bit pressure sensor (pres).

```
P=diff(pres);%Difference in counts
err=find(P<0);%Detect overscaling
P(err)=P(err)+2^24*ones(size(err));
      %Restore overscaling
P=[P(1); P];%Restore vector length
```

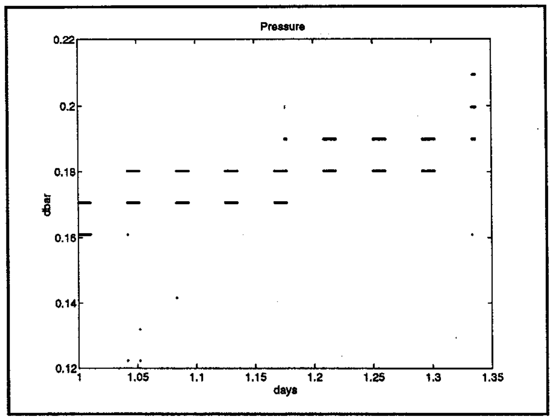

Fig. 2. Pressure from a Paros Digiquartz sensor the frequency of which was multiplied by 32 in a phase-locked-loop and sampled at 4 Hz by shifting the accumulated 24 bit count out of a serial shift register. Overscaling was restored by the algorithm above.

Multi-overscaling is a common occurrence in instruments that make measurements with short counters. The following code restores the multiple overscalings that effect Sea-Bird$_{TM}$ sensors with twelve bit counters (cbird) in the 250 ms between strobes. A test is made against the vector, scale, and if it is less than scale, another 2^12 is added. The value 1000 is based upon the expected temperature in the environment. When the temperature of the profiled area is unknown, the scale figure can be adaptively adjusted.

```
c = diff(cbird);
      %Difference in counts
c = [c(1,:);c];%Restore length
scale = [1000,1000];
ovscl = scale(ones(size(c,1),1),:);
loop = 1;
while (loop)
      index = find(c < ovscl) ;
      c(index) = c(index) + 2^12 *
ones(size(index));
      if (isempty(index)),
            loop = 0;
      end
end
c = c .* 4;%250 ms sample rate
```

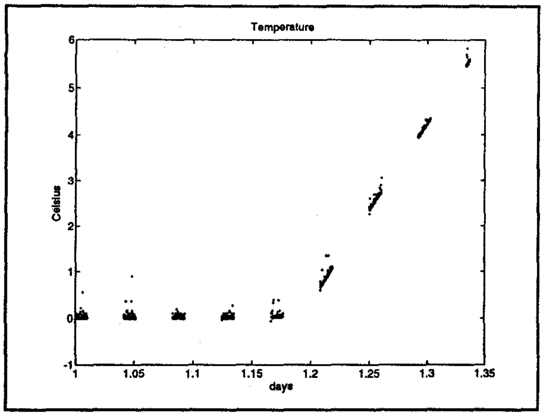

Fig. 3. Temperature from two Sea-Bird sensors sampled at 250 ms in a stirred ice bath. When the ice melted, both sensors tracked the warming water. Multiple overscalings of the counter between strobes occurred.

V. AVERAGING

In a situation in which the conditions being measured do not change rapidly, the precision of the data can be greatly increased by averaging over several sample intervals. For example, ocean temperature does not change greatly over time so it is an ideal measurement to use with this technique. This too can be done with Matlab, as below with Sea-Bird thermometers, sb:

```
sb_avg = zeros(size(sb));%Size array
for n = 1:[number of points],
      sb_avg(n,:)=mean(sb(n:n+10,1);
end
plot (n,sb_avg(n,:))
```

The bit noise of the counter sampling at 4 Hz in an icebath is visible in the 2000 points of Fig. 4. When a sliding average of ten samples is applied to these data (Fig. 5.), the resolution of the Sea-Bird temperature sensor is revealed to be at least 10 fold better and the temporal resolution is still 2.5 seconds.

VI. POTENTIAL PROBLEMS

Even when the sensor signal is clean, the output frequency from the latch (a high-speed CMOS device) is often contaminated with fast "commutating" transitions. These can be counted by a fast ripple counter like the 74HC4040 or even the slower CD4040. This produces too high a count. An RC filter between the latch and the counter removed this noise source in our counter.

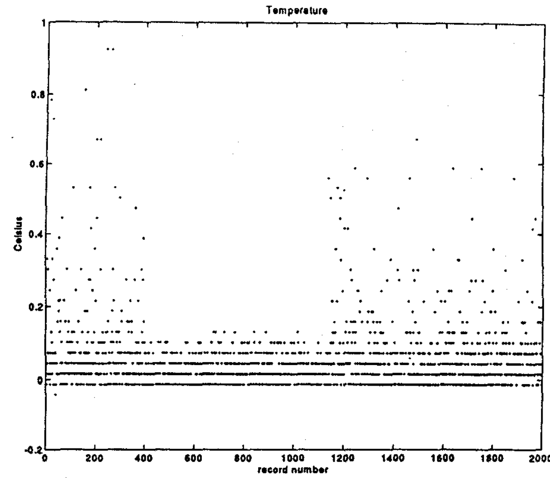

Fig. 4. Temperature sampled at 4 Hz in an icebath from a Sea-Bird temperature sensor.

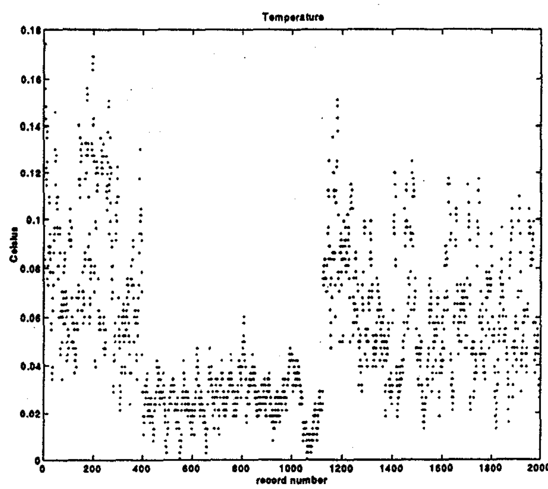

Fig. 5. The data of Fig. 4. averaged over ten points to give a tenfold improvement in resolution with 2.5 second temporal resolution.

There is the danger that with more than a certain number of serial shift registers, the shift clock will become loaded by the capacitance of the clock inputs and become too slow for accurate asynchronous clocking. The solution is to provide buffers for the serial shift clock every time the number of devices exceeds the fanout capability of the driver, typically eight. These shift clock buffers can be cascaded as long as the first stages to shift are those closest to the output. The risetime must be short, fully loaded, compared to the transition time of the serial shift register.

The PPL multiplier may lock on to an

inaccurate frequency and this may be counted in error. There are low frequency instabilities observed on our own PLL multipliers. Careful tuning and temperature testing is recommended to achieve the correct lock on.

The length of the counter is a trade off: too long and the propagation delay of the ripple counter will cause clock transitions to be missed during the strobe, too short and the ambiguity in the overscaling may cause the variable to be always in doubt. The speed of the strobe is a compromise. Too slow a strobe and clock transitions will be missed and the bandwidth of the measurement compromised. Too fast a strobe and ripple counts that have not settled will be latched into the shift register. Data recorded with this error are almost impossible to reconstruct after the fact.

An irregular or inaccurate strobe clock will contaminate the counting measurement by making the interval of counting unknown. Little can be done with this error after the fact as well.

VII. CONCLUSIONS

Instruments can obtain very precise and stable measurements from frequency output sensors with only a single penetrator per sensor (plus power and ground shared amongst all). The incremental cost in hardware and power is very low. PLL multipliers can solve resolution-bandwidth problems. Latches are needed to freeze the sensor signals while the counter outputs are strobed into the shift registers. Fast ripple counters are generally needed to propagate within a strobe time that does not lose pulses of the sensor signals.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Horowitz, P. and W. Hill. *The Art of Electronics*, The Cambridge University Press, 1990, pp. 641, 900.

[2] Ibid., pp. 156-158.

[3] Ibid., p. 524.

[4] Ibid., pp. 525-527.

[5] Ibid., p. 970.

[6] Ibid., pp. 579.

[7] Ibid., p. 541.