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The underwater section of the system includes underwater low light video cameras, a modulator, a single board IBM PC compatible computer, and a frame-grabber board. A demodulator, computers, frame-grabber boards, and monitors are included in the surface unit.
The uniqueness of this system is in the capability of sending a video signal with a bandwidth of 790 kilohertz over a cable which has a 56 dB loss at 1 hz. Also, it is necessary to send a 400 volt DC voltage down the cable in order to provide power to the underwater electronics. A vestigial sideband modulation method is used to transmit the video signal with an 833 kilohertz carrier. The cable itself and a surface equalizer are used to attenuate the upper sideband sufficiently in order to recover the video signal with an envelop detector at the surface. The latter includes a unique sample-hold circuit which effectively provides full wave rectification of the modulated carrier with a high bandwidth.

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A VIDEO TELEMETRY SYSTEM FOR DEEP OCEAN USE

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ABSTRACT

A video system for use in deep ocean areas has been designed and prototyped. The basic specifications for the system include the use of a single coaxial cable for towing a camera sled, providing sled electrical power, and allowing the transmission up the cable of video images at a rate as near real time as possible.

The underwater section of the system includes underwater low light video cameras, a modulator, a single board IBM PC compatible computer, and a frame-grabber board. A demodulator, computers, frame-grabber boards, and monitors are included in the surface unit.

The uniqueness of this system is in the capability of sending a video signal with a bandwidth of 790 kilohertz over a cable which has a 56 dB loss at 1 Mhz. Also, it is necessary to send a 400 volt DC voltage down the cable in order to provide power to the underwater electronics. A vestigial sideband modulation method is used to transmit the video signal with an 833 kilohertz carrier. The cable itself and a surface equalizer are used to attenuate the upper sideband sufficiently in order to recover the video signal with an envelope detector at the surface. The latter includes a unique sample-hold circuit which effectively provides full wave rectification of the modulated carrier with a high bandwidth.

Video signals have been sent over a 9 kilometer coaxial towing cable at the rate of four frames per second with very good quality. The system also includes frequency-shift-keying (FSK) commands which can be sent from the surface to the underwater package and vice versa. This capability allows simultaneous transmission of video signals and the ability to change cameras, turn on underwater spotlights, etc.

key words: vestigial sideband, equalization, tow cables

I INTRODUCTION

The underwater television system described in this paper is used to convert low level light underwater television images into a slow scan output signal which is used to transfer the images via a towcable telemetry system to the deckside system where the slow scan signals are reconverted to a standard television signal format and displayed on a television monitor. The underwater system consists of two monochrome low level light television cameras, two incandescent light sources, two video S-VHS tape recorders, and the controller and scan converter electronics. The deckside system consists of a controller and scan converter computer system, an image processing computer system, two S-VHS tape recorders, and two monochrome television monitors.

The television system has many remote control features which allow an operator to tailor the system to the changing requirements of an underwater operation. Both underwater cameras can be independently adjusted for lens focus and zoom (17.5 to 105mm). Both light sources have selectable 40, 60, and 100 watt settings. Both underwater S-VHS recorders can be independently commanded to record the output (30 frames per second, RS-170 format, on the Y input of the S-VHS recorder) of a designated underwater camera for playback upon recovery of the equipment. The image pixel transfer rate of the system can be varied which allows compromises on the image vertical resolution (maximum 512 pixels per scan line) versus image update rate (maximum 7 frames per second) based on the telemetry video channel bandwidth and pixel transfer rate.

The deckside system is used to control the underwater system, record and playback the converted slow update rate underwater images, playback the recordings made by the underwater S-VHS recorders, and allow image processing of the recorded images. The deckside and underwater recorders store on their audio channel all the uplink and downlink telemetry between the underwater and deckside systems. The image processor computer can capture an image as it is generated by the circuits in the controller computer or from the playback of a recorder. Once the image is captured by the image processor computer the image can be manipulated by the computer system for maximum image enhancement.

The towcable is an armored coaxial cable with characteristics similar to RG-8 coaxial cable. The length is approximately 9 kilometers, which provides tow depths in the range of 6 kilometers. The measured attenuation in the towcable is 65 dB at 1 megahertz. Since the desired video bandwidth is 790 kilohertz and it is required to have a DC power signal on the cable, a technique has been devised to equalize the cable and maintain an acceptable signal to noise ratio. This telemetry system which is used to transmit video data from the underwater computer system to the deckside computer system is based on the vestigial sideband modulation technique. A modulator contained in the underwater unit modulates a carrier using a conventional large carrier content amplitude modulation circuit. The deckside component of the telemetry system contains an equalizer and a demodulator which recovers the video signal.

II SYSTEM REQUIREMENTS

A major portion of the hardware and software used in this project existed before the addition of the video and telemetry links described here. In the underwater unit, a sled and pressure vessels used on another project were modified to function as a video unit consisting of the two cameras, lights, a PC, power supply, and the video recording and processing equipment. The essential change specified that the modulated video signal could occupy the majority of the cable bandwidth, in contrast with the previous specification which allowed only 268 kilohertz of modulated bandwidth and the video signal bandwidth was limited to only 50 kilohertz. Thus, the basic requirement was to design a system to send video signals from the underwater camera unit to the deckside unit. It was also required that FSK signals could be sent in a half duplex manner uplink and downlink to effect control over the lights and cameras.

The cable length of 9 kilometers was fixed, along with the use of the cable itself. No additional cabling could be used. Thus, it was required to design the system such that:

- power is transferred to the underwater unit to operate the cameras, lights, electronics, etc. by the use of a single coaxial cable.
- the video signal is transmitted on the coaxial cable.
- the transfer rate of the video information is as fast as practicable with the given coaxial cable bandwidth.
- a reliable FSK uplink and downlink channel is provided; half duplex is acceptable.
- existing hardware and software is used whereever possible.

In view of these requirements, the system was designed as detailed below.

III SYSTEM DEFINITION

A block diagram of the underwater portion of the video telemetry system is shown in Figure 1. As shown in this figure, the camera (one of the two cameras selected by the computer) is connected to the frame-grabber board. Software is included in the computer which controls the frame-grabber and the analog electronics needed to generate the video output signal, $m(t)$. The latter is a *0-5* volt analog signal which represents the value of each pixel of the image captured by the frame-grabber as the pixels are scanned. A synchronization signal is generated in $m(t)$ to indicate the beginning of a frame scan. Each pixel value stored by the frame-grabber is converted from an eight bit word to an analog value by a digital to analog converter (D/A).

An offset is added to a scaled $m(t)$ to generate $m'(t)$. This signal is then applied to a commutator consisting of CMOS analog switches S_1 and S_2. These switches are controlled by an 833 Khz clock. One switch is alternately opened and closed by the square wave signal $CLOCK$ and the other switch is operated by the inverted signal $\overline{CLOCK}$. The net result is a large carrier double sideband (DSB) signal [1]

$$\begin{aligned} x(t) &= (1.5 + 0.5m(t))\cos\omega_c t & (1) \\ &= 1.5(1 + 0.33m(t))\cos\omega_c t & (2) \end{aligned}$$

where $\omega_c = 2\pi f_c$ and $f_c = 833\ Khz$. The percent modulation is defined by [2]

$$\%modulation = \frac{max\ magnitude - min\ magnitude}{max\ magnitude + min\ magnitude} 100\% \quad (3)$$

where the magnitude refers to the magnitude of the modulated carrier in (2). Using the minimum and maximum values of $m(t)$ as 0 and 5 *volts* respectively, gives a percent modulation of 45.5%. This can also be seen by substituting a single tone modulation signal of

$$m(t) = 2.5\cos\omega_m t + 2.5 \quad (4)$$

into equation (2). This expression for $m(t)$ represents a $0 - 5volt$ cosine video signal. The expression for $x(t)$ becomes

$$x(t) = 2.75(1 + 0.455\cos\omega_m t) \quad (5)$$

The coefficient, 0.455 = 45.5%, of the modulating cosine is the percentage modulation. The modulation is intentionally kept to a low percentage to minimize the distortion in the demodulation process. As shown in Figure 1 the FSK Uplink Output is passed through a $5\,Khz - 15\,Khz$ band pass filter (BPF) and added to the modulated carrier. The total signal is then applied to a matching network which has a 50Ω equivalent impedance.

The coaxial cable is connected to the modulator matching network through a DC blocking capacitor. A BPF similar to the one above is connected to the capacitor on the same side as the matching network. This BPF is used to filter out the FSK signals on the coaxial cable being sent by the deckside computer, down the cable, to the underwater computer. A DC voltage in the range of $300 - 400\ VDC$ is applied to the coaxial cable by the deckside system. This voltage is used to provide the power for the entire underwater system. DC to DC converters are used to convert the high DC voltage to usable low level voltages such as $\pm 12\ VDC$ and $5\ VDC$.

It should be noted here that the presence of the DC voltage on the cable is the reason that a baseband transmission of the video signals is not possible. In order to pass the complete video bandwidth it is necessary to include DC in the video passband. For example, any portion of the picture to be transmitted which is of constant luminance will have a constant modulation signal amplitude. This portion of the transmission has a DC component. With the power signal present it is impossible separate the power DC signal from the DC component of a baseband video signal. Thus, it was decided to modulate the video signal up to 833 Khz and use the low frequency passband, up to approximately 15 Khz, for the FSK signals.

The Demodulator system is shown in Figure 2. The coaxial cable is connected to the high voltage power supply through a choke which prevents shunting of the FSK and video signals through the power supply. The high voltage is prevented from being applied to the signal matching network by a blocking capacitor. The matching network is used to match the input buffer and the FSK driver to the coaxial line. An amplifier stage H_1 is used to isolate the remainder of the equalizer and the FSK low pass filter (LPF), from the matching network.

The equalizer is used to compensate for the attenuation by the coaxial cable of high frequencies. The approximate frequency response of the cable is shown in Figure 3. This response was obtained by measuring the actual sinusoidal response of the cable at various frequencies between 10 Khz and 1 Mhz and matching a transfer function to the given magnitude response measurements. The transfer function for the frequency response shown in Figure 3 is given by

$$T(s) = 0.43\frac{1}{(\frac{s}{2\pi 40K} + 1)(\frac{s}{2\pi 625K} + 1)^3} \quad (6)$$

This transfer function was obtained by first plotting the measured frequency response and matching straight line approximations to the curve. A frequency response of an actual transfer function obtained from the straight line approximations was then compared to the actual measurements. The poles of the transfer function were iteratively changed until the frequency response of the transfer function matched the measured data to within 0.82 dB. [3]

It can be seen from (6) that the cable exhibits the behavior of a system having a break frequency at 40 Khz and a triple break frequency at 525 Khz. Thus, the required equalization involves the use of zeros in H_1, H_2, and H_3 to cancel the effect of the poles in $T(s)$. These three stages were essentially tuned for the coaxial cable to provide the desired frequency response. Since the modulation signal is recovered with an envelope detector, the equalization must be carefully designed to ensure the proper attenuation of the upper sideband. This technique of suppressing one sideband is called vestigial sideband modulation. [4] The most common example of this technique is the transmission of video signals by commercial broadcast television stations. The upper sideband is not completely attenuated, but rolls off at a rate which allows the recovery of the lower sideband signal by simple envelope detection. The equalizer transfer functions which were successfully used are

$$H_1(s) = H_2(s) = \frac{\frac{s}{2\pi 816K} + 1}{\frac{s}{2\pi 936K} + 1} \tag{7}$$

$$H_3(s) = \frac{\frac{s}{2\pi 32K} + 1}{\frac{s}{2\pi 3.180M} + 1} \tag{8}$$

The cascade combination of these three transfer functions provided the correct high frequency emphasis which compensated for the high frequency loss of the coaxial cable. The combination of the loss of the coaxial cable and the gain of the equalizer provides what is known as a *vestigial shaping filter*. [4] Note that the equalizer required only three zeros, two high frequency and one low frequency. The cable exhibited a four pole behavior. Thus, the high frequencies contained in the upper sideband were attenuated both by the cable and by the additional high frequency poles in the equalizer.

The envelope detector consists of peak detectors and zero crossing detectors with a sample and hold (S/H). The output of the equalizer and its inverse are sent to zero crossing detectors which provide very narrow pulses whenever their inputs cross zero from a positive value to a negative value. The pulses are used to close pairs of CMOS analog switches. One switch of each pair is connected to a holding capacitor and the other switch is connected to the output of the opposite peak detector. The peak detectors are used to detect the peak values of each half cycle of the modulated carrier. The value of the peak detector output is transferred to the holding capacitor at the *beginning* of the next half cycle. Simultaneously, the other peak detector output is set to zero by the second switch in the pair. At the *end* of the next half cycle, the peak detector output is set to zero and the process is repeated.

The S/H, consisting of the peak detectors, switches, and the holding capacitor, provides a signal which is the envelope of the modulated carrier. By detecting alternate half cycles of the signal, a full wave rectification is performed, ensuring that the modulated signal is sampled at twice the carrier frequency and not at carrier frequency which would be the case if only the positive half cycles were used, or half wave rectification. The latter is the usual method used in envelope detection. Half wave rectification is effective if the carrier frequency is much greater than the highest modulating frequency. A low pass filter is used in the latter case to filter out the carrier component from the detected signal. In this case, however, the carrier frequency is not much greater than the highest modulating frequency; i.e. 833 Khz versus 790 Khz. The use of a low pass filter to remove the carrier component is impractical.

The sampling process described above generates significant harmonics at twice the carrier frequency. A simple *Sallen and Key* lowpass filter is used in the final stage to generate the demodulator output. [5] An offset and gain adjustment is used to adjust the contrast and brightness of the displayed picture on the monitor. A frame grabber board, which is a duplicate of the one used in the underwater system, accepts the raw demodulated signal and generates the actual video signal which is sent to the monitor. Synchronization information is provided by the demodulated signal.

FSK signals are sent and received in the 15 Khz bandwidth above DC. The equalizer incorporates a four pole 40 Khz filter (which is not shown in equations (7) and (8)) in order to keep the FSK signals from interfering with the video signal amplification in the equalizer.

IV SYSTEM PERFORMANCE

The system described above has actually been prototyped and laboratory tested. The input to the modulator is either a VCR signal or a computer generated bar test pattern. A 9 kilometer cable wound on a spool is used to connect the modulator to the demodulator. The demodulator is used to detect the signals on the cable and drive a computer containing a frame-grabber board. The output is sent to a high quality CRT monitor.

Required adjustments to the system are minimal. The modulator unit only requires the adjustment of one gain setting in order to ensure a symmetrical modulated carrier. The carrier clock is crystal controlled and, therefore, requires no adjustment.

The demodulator requires several adjustments which are easily made. The first is the shaping of the equalization. Plug-in capacitors are used to adjust the zeros and poles of the H_1, H_2, and H_3 stages. Two capacitors for each stage are chosen to obtain minimum distortion in the video output. A spectrum analyzer can be used very effectively in finding the optimal values. The two zero crossing detectors which are used to drive the two pairs of CMOS analog switches are adjusted to provide the correct pulse width in order to completely transfer the output of one peak detector to the holding capacitor, and to completely discharge the opposite peak detector. These adjustments are easily made with a fixed sine wave modulator input.

The only remaining adjustments are the output gain and offset. As mentioned previously, this affects the brightness and contrast of the video output.

After making the required adjustments, a series of test patterns and VCR inputs were transmitted through the system. The performance was excellent. Video pictures were sent at the rate of four per second with excellent clarity and dynamic range. The measured signal to noise ratio was better than 48 dB.

V CONCLUSIONS

The system requirements detailed above have been achieved by the design of the electronic modulator-demodulator described here. A prototype has been built and tested and is ready for field use. The vestigial sideband modulation technique has proved to be an excellent choice. Judicious choice of equalization allows the suppression of the upper sideband in such a manner that an envelope detector recovers the video signal with a minimum of distortion. Proper filtering of the FSK signals keeps these signals from interfering with the video signals. No measurable crosstalk is present between the FSK signals and the video.

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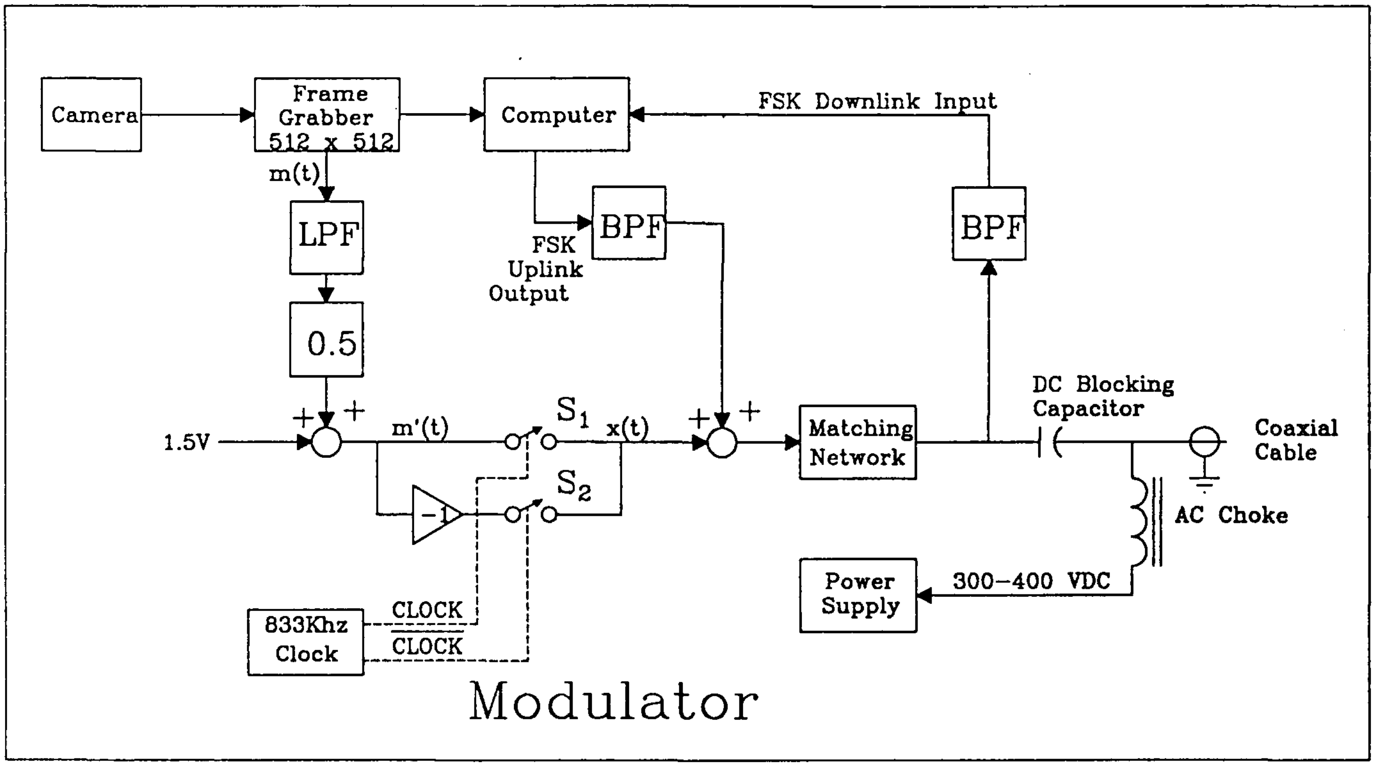

Figure 1. Block diagram of the underwater portion of the telemetry system.

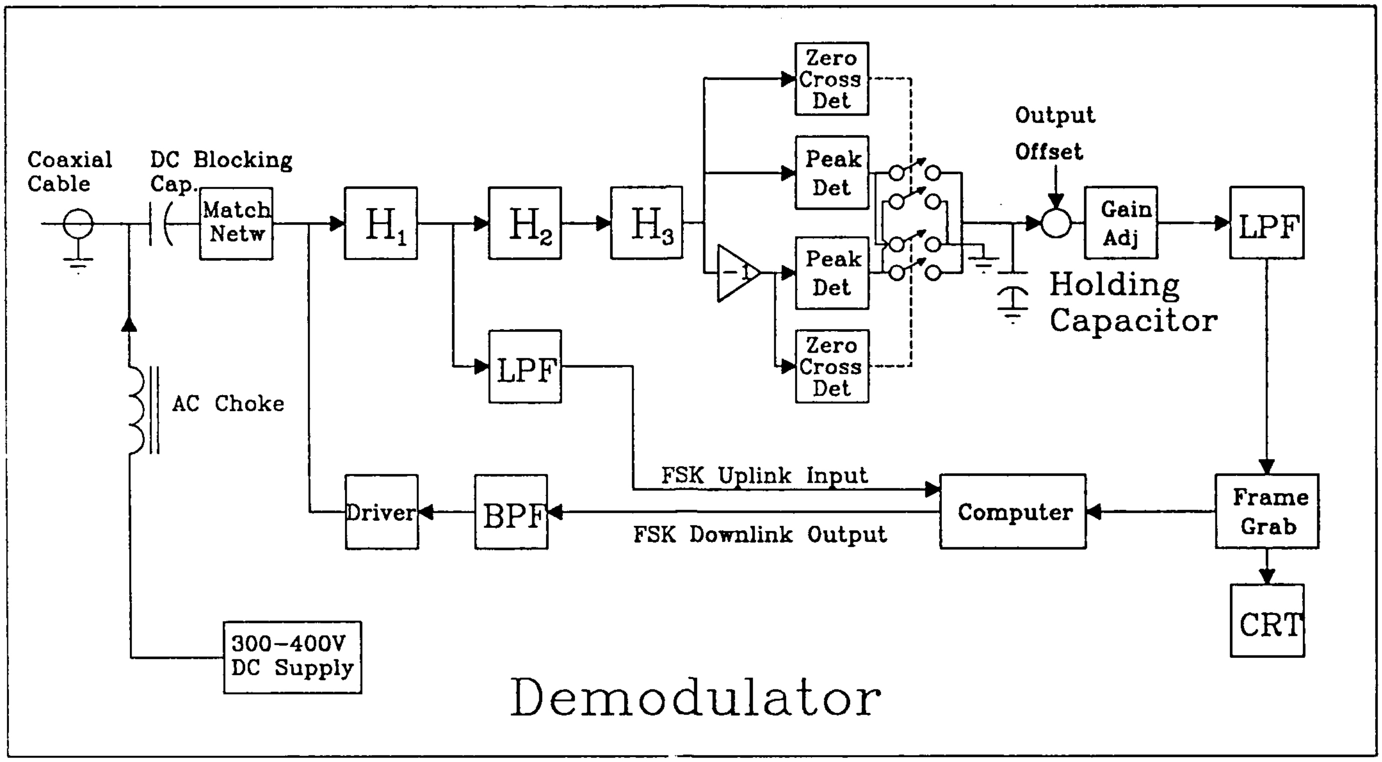

Figure 2. Block diagram of the deckside portion of the telemetry system.

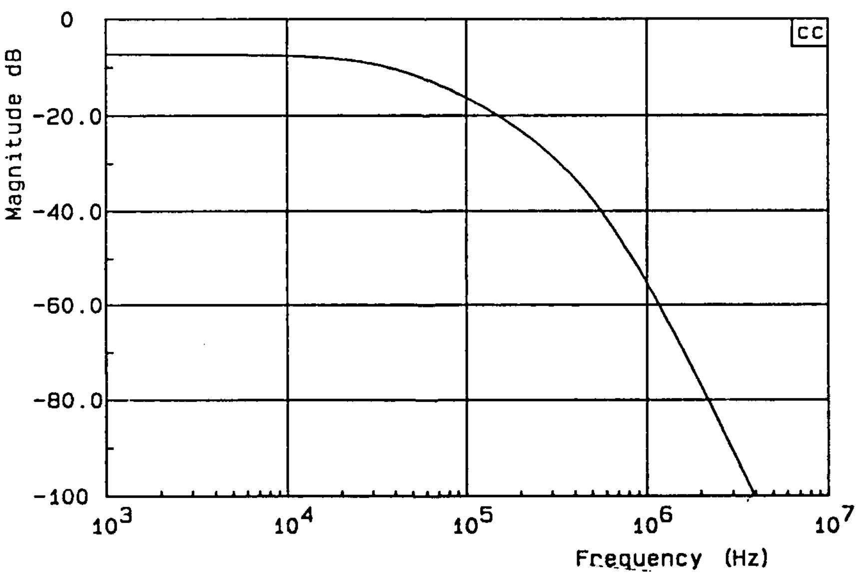

Figure 3. Magnitude response of the transfer function, $T(s)$, used to model the coaxial cable.