Multiple document detection with ultrasonics

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MULTIPLE DOCUMENT DETECTION WITH ULTRASONICS

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Multiple Document Detection with Ultrasonics

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ABSTRACT

The purpose of this thesis was to develop a method to detect the occurrence of more than one document being drawn into an automatic document feeder such as is used on photocopiers and document scanners. It was desired that the method developed made no physical contact with these documents, worked with all common document materials and thicknesses. The method actually developed monitors the amplitude and phase changes in ultrasound passed through these documents. By using both the amplitude and phase of the ultrasound, a material and thickness independent method, non contact method was successfully developed.
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1 INTRODUCTION

1.1 Document Transports

In a document transport system with an automatic document feeder, the documents are automatically fed from a paper storage tray into the document transport. This allows the system to operate without user interaction. This type of system is needed in the situation where many documents are to be handled. An example of an automatic document feeder is the paper supply in a copier. The "ultrasonic document detector circuit" addresses the document transport used in a document scanner.

The document transport in a copier has a tremendous advantage over the transport in a document scanner. The paper used in a copier is new and at most two different sizes and all the same thickness[1]. The transport in a document scanner must be able to handle paper which includes onion sheets, 110# bond, 20# bond, photographs, newspaper and even thin cardboard. Varying sized documents must also be handled from short documents, including checks and business cards, up to very long documents such as electrocardiograms. In short, a document scanner must handle any type of document that will be processed or stored electronically including old and dirty documents.
1.2 Multiple Documents

In the ideal situation, only a single document will be fed into the document transport at a time. In less than ideal situations, more than one document can be fed into the document scanner by the automatic document feeder resulting in multiple document feeds. Multiple document feeds can be caused by static buildup between the documents, documents with rips or tears, wet documents sticking together, staples, high friction paper such as carbon paper, buildup on the mechanical parts feeding the documents and sticky labels.[1]

When there is a multiple document feed in a document scanner, there is data lost. If two or more documents are fed at the same time, only the document facing the scanning device will be scanned and the other document will pass through unscanned. This can result in lost revenue for a business if they used this scanned information for their billing. The problem can be more serious if these documents are incorrectly scanned and the originals are then destroyed. It is very common to destroy the documents after they are scanned since the data can be stored electronically for large cost and space savings.

1.3 Present Multiple Document Detection Methods

Numerous methods are used to detect multiple document feeds. One method involves rescanning all the documents fed in a batch a second time in a "count only mode". The document scanner counts the number of documents on the
initial scan and then counts the documents on the second time through the transport without saving the scanned images. If these two numbers do not agree, then there is at least one multiple document feed on one of these two processes. This results in twice the time to process the documents. Finding the actual multiple document feed(s) can also be very time consuming, since it is not known which document(s) was not scanned. This method does have the advantage of being document-independent as will be discussed in detail.[2]

A second method involves measuring the thickness of the documents with a sensing arm or "contact foot". This "paper contact method" continuously measures the thickness of the paper passing through the transport. If the measured thickness increases above a set level, it is assumed that there is a multiple document feed. The sensor can be a Linear Volt Differential Transducer (LVDT) or a Hall Effect Sensor that will be explained in greater detail in Chapter 2. This method requires that only a single paper thickness is scanned and that all the documents scanned are of the same thickness. Two onion sheets are thinner than one regular sheet of 20# bond and would pass through undetected if the system is calibrated for 20# bond. Also, since there is a "contact foot" in physical contact with moving paper, paper jams are more common.[1] This method has the advantage of not slowing the scanning process as in the "count only method" above. The circuitry required for the "paper contact method" is approximately the same complexity as the approach taken for the "ultrasonic document detector circuit" explored in detail here.
A non-contact method that detects multiple document feeds is the "ultrasonic amplitude method". This involves passing ultrasound through the document(s) and measuring the attenuation of the received ultrasonic signal. Since the ultrasound level decreases with each document it passes through and with each air to document interface it encounters, the presence of multiple documents can be detected. This eliminates the paper jamming problem caused by the "paper contact method" above while not slowing the scanning process as in the "count only method". However, it is not document-independent since a single sheet of thick paper can have more attenuation than two sheets of thin paper.

1.4 Approach Taken

In the testing performed for the development of the "ultrasonic document detector circuit", the "paper contact method" was found to offer better results for detecting multiple document feeds than the "ultrasonic amplitude method". However, there are wear problems with the "contact foot" that touched the paper and the "contact foot" needs to be replaced after approximately 100,000 documents.[2] This could range from a few years to a few days depending on usage.

An ideal method would not slow the processing time, would not require periodic parts replacement and would be document-independent but still detect a very
high percentage of the multiple document feeds and not indicate false multiple
document feeds. These constraints ruled out all of the above methods. The
"count only method" has a large reduction in document throughput. The "paper
contact method" causes paper jams, is not document-independent and requires
replacement of the contact parts. Finally, the "ultrasonic amplitude method" is
neither accurate enough nor document-independent.

The "ultrasonic amplitude method" offered the most advantages and was,
therefore, used as the starting point for is the "ultrasonic document detector
circuit". During testing, it was determined that the phase of the received signal
was dependent on the number of documents between the ultrasonic transmitter
and ultrasonic receiver. Additional research indicated some work had been
done at Eastman Kodak Company with phase shift alone to test for the
presence of multiple documents.[3] This provided additional data that could be
used to detect the presence of multiple document feeds.
2 REVIEW OF LITERATURE

The design described in this work utilizes a closed loop system that contains both analog and digital electronics with sound waves in the feedback path as shown in the block diagrams in Figures 1 and 2. This requires a frequency generator and driver circuit, an analog receiver, analog processing circuitry, a phase detector, an amplitude detector, a microcontroller with support circuitry and an ultrasonic transmitter and ultrasonic receiver. All of this circuitry is straightforward except for the phase detector and the ultrasonic transmitter and ultrasonic receiver, which are explained below. Additional details of all of the subsystems are provided in the design section.
Figure 1 Block Diagram, Original Approach
2.1 Phase Detection

As described in Chapter 1, the requirement exists in the "ultrasonic document detector circuit" to measure the phase difference between the signal driving the ultrasonic transmitter and the signal detected at the ultrasonic receiver. A reference phase difference between these two signals, with no paper within the ultrasound path, is determined during a calibration process and used as the baseline by the decision algorithm within the microcontroller. The difference
between this baseline and the measured signal with paper in the ultrasound path is the phase shift due to that paper. This algorithm, which is executed within the microcontroller, determines the presence of multiple document feeds using this phase shift information. The larger the range of the phase differential that can be measured, the higher the number of documents for a multiple document situation that can be accurately determined, and the less the chance of a phase wrap around situation.

Phase wrap around occurs when the total phase shift is more than the phase shift that can be measured by the phase detection method. For example, if each document within the detection path was to cause a 90-degree phase shift and four documents were present, that total indicated phase shift would be 360-degrees. If the phase shift detection method could measure a full 360-degrees of phase shift, up to three documents could be detected before phase wrap around occurred. This would result in four documents indicating the same phase shift as no documents. The phase shift detection methods that can only measure 180-degrees of phase shift are not an option since the presence of two documents would have the same indicated phase shift as no documents due to phase wrap around.

A phase detector is a form of a comparator that provides an output signal proportional to the difference in phase of two input signals. Ideally this output is
a DC signal which can be easily interrupted by the controlling circuitry. This is written as follows:

\[ V_p = K_p (\phi_1 - \phi_2) \]  \[4\] where

- \( V_p \) is the output voltage.
- \( K_p \) is the phase detector gain in volts per radian.
- \( \phi_1 \) and \( \phi_2 \) are the phases of the input signals, \( V_1 \) and \( V_2 \).

The two basic types of phase detectors are the multiplier and the sequential detectors.[5][6][7] The multiplier phase detector has an advantage in an application where the input signal is noisy, whereas the sequential phase detector has an advantage in frequency tracking performance. A comparison of the multiplier and sequential phase detectors is shown in Table 2.1.[4]

Examining Table 2.1 shows that the multiplier phase detector is superior in the areas of working in a noisy environment, has the ability to 'flywheel', and has the capability of harmonic locking. In the "ultrasonic document detector circuit" application, the environment is low noise and harmonic locking is not an issue since both signals are the same frequency. The sequential phase detector is superior in the areas of capture range, tracking and range of duty cycle of the input signal. From these characteristics alone, there is no clear advantage to either method. What does give the sequential phase detector an advantage in
this application is the ability to measure 360-degrees of phase shift whereas the multiplier phase detector will only measure 180-degrees of phase shift. The range of interest for phase shift in this application is approximately 100 to 360-degrees since this is the frequency range covering from one to three documents. Therefore, the sequential phase detector is the method of choice. Both methods are described below.

<table>
<thead>
<tr>
<th>Property</th>
<th>Multiplier Phase Detector</th>
<th>Sequential Phase Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance at S/N&lt;10dB</td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td>Ability to “flywheel”</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Capability of Harmonic</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Locking</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capture Range</td>
<td>Poor</td>
<td>Good to Excellent</td>
</tr>
<tr>
<td>Tracking</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Optimum Duty Cycle of Input</td>
<td>50%</td>
<td>Not important</td>
</tr>
<tr>
<td>Signals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC Output Component Frequency</td>
<td>Twice Input Frequency/High</td>
<td>Input Frequency/Low</td>
</tr>
<tr>
<td>and Level</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase Offset in a Locked Loop</td>
<td>90-degrees</td>
<td>0 or 180-degrees</td>
</tr>
</tbody>
</table>

Table 2-1 Comparison of Multiplier and Sequential Phase Detection
2.1.1 Multiplier Phase Detector

The multiplier phase detector uses the product of two alternating input signals where the DC component is dependent on the phase difference between these two signals.[4] The multiplier approach is a linear method that makes use of an analog multiplier to produce the product of the two input signals, V1 and V2. The result of applying these two signals to a multiplier is shown below:

**Inputs:**

\[ V_1(t) = V_1 \cos \omega t \quad \text{and} \quad V_2(t) = V_2 \cos(\omega t - \phi) \]  \[4\]

\[ V_p(t) = KV_1(t)V_2(t) = (KV_1V_2/2)\left[ \cos(2\omega t - \phi) + \cos(\phi) \right] \]  \[4\]

**Where:**

K is the gain constant.

\( \phi \) is the phase difference of the two input signals.
The output consists of a DC term, \( \cos(\phi) \), and a double-frequency component, \( \cos(2\omega t - \phi) \). The double-frequency component is filtered out which leaves the DC term:

\[
V_p = (K*V1*V2/2)*[\cos(\phi)]
\]

The above equations demonstrate that a multiplier phase detector's output varies sinusoidally with the phase differential. There are zeros at \( \phi = \pi/2 + n^*\pi \).

A multiplier phase detector will also work well with one analog and one digital input. This would be useful in the "ultrasonic document detector circuit" that uses a digital signal to drive the ultrasonic transmitter and receives the signal from the ultrasonic receiver in the analog form of a sinewave. With two digital inputs applied, the multiplier phase detector would function as an exclusive-NOR logic function and would interface directly to digital circuitry.

2.1.2 Sequential Phase Detector

The sequential phase detector responds to the relative timing on the edges of the input signals and is implemented in digital form. Shown in Figure 3 is an RS flip-flop phase detector. The flip-flop is set on the rising edge of V1 and reset on the rising edge of V2. This results in the mean DC level of the output of the flip-
flop providing an indication of the phase difference between the two input signals. The output from the flip-flop is sent through a low pass filter and the resulting DC value has a linear relationship between the phases of these two signals. However, since this method works on the rising edges of the input signal, high levels of noise on either input will result in errors in the indicated phase differential.

Figure 3 Flip-Flop Phase Detector

An alternate method for sequential phase detection is shown in Figure 4. This was the analog approach taken for the "ultrasonic document detector circuit" until the method was redirected to use a digital approach for phase detection as will be described in detail later. Referring to the waveform in Figure 4, if V1 initially leads V2 by \( \phi \), then after each positive edge on V1, Q1 is set to a '1'.

14
With the next rising edge of $V_2$, both $Q_1$ and $Q_2$ are set to '1'. With both inputs to the AND gate equal to '1', the flip-flops are both reset to '0'. If $V_1$ leads $V_2$, the mean value of $Q_1$ indicates the amount of phase lead. If $V_1$ lags $V_2$, the mean value of $Q_2$ indicates the amount of phase lag. The output at $Q_1$ and $Q_2$ can be summed to produce a phase detector with a linear range of $4\pi$ radians. However, only the phase lag is used in the "ultrasonic document detector circuit" with the result that a lag of $2\pi$ can be detected with this approach. This offers an improvement over the $1\pi$ range that could be detected with the multiplier phase detector. Figure 5 shows the results obtained from this circuit during testing. The output is linear with respect to the phase difference.
Figure 4 Sequential Phase Detector
2.2 Ultrasonics

Ultrasonics is the range of frequencies above the hearing range of the average person. This range is approximately 16 kHz to 500 MHz. Some typical applications of ultrasonics are for plastic welding (16 to 25 kHz), cleaning (20 to 400 kHz) and surgical applications (900 kHz to 5 MHz).[8] Generally, higher frequencies are used when higher particle acceleration combined with lower particle displacement is needed. Higher frequencies are also more sharply focused as they propagate. Lower frequencies are used for achieving maximum particle displacement for applications such as cleaning.
An ultrasonic transducer produces the ultrasound waves. The three main categories of ultrasonic transducers are: electromagnetic, magnetostrictive and piezoelectric.[9] An electromagnetic transducer works by applying the ultrasonic frequency to a coil that is in a magnetic field. This results in the coil moving or vibrating at the applied frequency. An example of this type of transducer is the electrodynamic loudspeaker. A magnetostrictive transducer is produced by winding a coil of wire around both arms of a support assembly called a stack. When alternating currents are passed through the coil, the changing magnetic fields causes the stack to vibrate at two times the applied frequency (one vibration for the high going signal and one for the low going signal). The most common method used for ultrasonic transducers is piezoelectric. That approach is used in this paper because of the low cost and the simple electronic drive circuitry required.

2.2.1 Piezoelectric Transducers

The piezoelectric effect uses crystals to change energy between the form of mechanical and electrical energy. Pierre Curie discovered piezoelectricity in 1880.[8] The most common piezoelectric substances used in ultrasonics include quartz, barium titanate, lead zirconium titanate, Rochelle salt and ammonium dihydrogen phosphate. Vibrations are caused in piezoelectric materials by applying a voltage, causing the crystal domains to align. These
crystal domains go back to their previous position when the voltage is removed. By applying a voltage at the resonant frequency of the piezoelectric material, the material vibrates.[8]

The ultrasonic receiver works on the same principle as the ultrasonic transmitter in reverse; the ultrasonic receiver produces a voltage when there is a pressure or ultrasonic wave in the range of its resonant frequency applied to it. Often the ultrasonic transmitter and ultrasonic receiver are interchangeable. Many manufacturers of ultrasonic transducers screen their transducers for impedance at the resonant frequency. Those with low impedance at the resonant frequency are used for the transmitters and those with high impedance at the resonant frequency are used for the receivers.[10] The lower impedance in the transmitter allows more current to flow into the transducer resulting in more ultrasonic energy being produced for an applied voltage. The higher impedance in the receiver produces a higher output voltage in the receiver for a given sound level being applied.

The driving signal used in the "ultrasonic document detector circuit" is a squarewave for the transmitter and the received signal is a sinewave. A squarewave is used to simplify the required drive circuitry. The ultrasound waves produced by the transmitter are in the form of a sinewave even with squarewave drive. This is because a squarewave is the combination of an infinite number of odd order harmonic sinewaves and all but the resonant
frequency are effectively ignored by the transmitter due to the reduction in the transmitted energy at even a fraction of a wavelength away from its resonant frequency. The receiver also has this same effect resulting in an attenuation of the received signal that is not at its resonant frequency. Figure 6 shows the rate of falloff of the ultrasonic transmitter and ultrasonic receiver as the frequency changes from the resonant obtained during the test phase. The results in this figure agree with those found in the vendor data sheets on the ultrasonic transmitter and ultrasonic receiver.

![Graph showing Receiver Output vs. Frequency without Paper](image)

**Figure 6 Receiver Output vs. Frequency without Paper**

Quartz crystal is often used for the piezoelectric transducer because it is able to withstand high voltage, high power and high temperature, is physically strong and is nonhygroscopic. In addition, quartz transducers have efficiencies of
approximately 90%. Quartz is cut into small crystals where the frequency of oscillation is dependent on the final shape of this crystal.

2.2.2 Attenuation of Ultrasound

The second analog input to the microcontroller in the "ultrasonic document detector circuit", for use by the decision algorithm, is the amplitude of the received signal generated by the ultrasonic detector. There are several factors that attenuate the ultrasonic signal between the ultrasonic transmitter and ultrasonic receiver and, therefore, reduce the amplitude of the received signal.[9] This signal is attenuated by the absorption of the energy between the ultrasonic transmitter and ultrasonic receiver and by the deflection of the ultrasonic energy by reflection, refraction, diffraction and scattering. In short, for a reduction in the level of the received signal, the ultrasonic waves are either absorbed or steered away from the sensor.

Higher frequency ultrasonic waves are more directional.[8] The waves emitted from this transducer are directional because each section of the wave leaving the surface of the transducer takes approximately the same time to arrive at the ultrasonic receiver. There are no out-of-phase waves propagating in the direction of the ultrasonic receiver (assuming both the ultrasonic transmitter and ultrasonic receiver are in the same plane) and, therefore, no cancellation takes
place between the waves in this direction.[8] Phase differences of the waves leaving in a non-planar fashion are cancelled because the distance traveled is different, resulting in phase differences. This has the effect of being able to “point” the ultrasonic waves in a desired direction and to concentrate the energy. It is also possible to point the ultrasonic waves with a sound lens to send more of the sound energy in the desired direction.[8]

In the design of the "ultrasonic document detector circuit" presented here, the attenuation due to air is very small, since the distance the ultrasound passes between the ultrasonic transmitter and ultrasonic receiver is very short. Since this value is relatively constant with time, the small changes in the absorption by air are compensated for by the self-calibration routine as will be described in Chapter 3.

2.2.3 Applications and Uses of Ultrasonics

The basic application groups of ultrasonics include cavitation, echo-ranging and miscellaneous applications.[8] Cavitation results when high-power ultrasonic waves are applied to a liquid such as water. The molecules in this liquid become agitated and this agitation causes the formation of small vapor bubbles that implode, releasing tremendous local pressures. Applications using cavitation ultrasound include cleaning, soldering, drilling, degassing and
emulsification. Ultrasonic echo-ranging is the transmission of ultrasound into a medium and the reception of the returned echo from an object that reflects some of the ultrasonic energy. The strength of the reflected energy and the time to receive the reflection provides information about the object reflecting that energy. The object causing the reflections could be a submarine or a flaw in a metal casting. Common uses of the echo-ranging method include fishscopes to find fish and thickness gages to measure the thickness of solid objects. Some of the miscellaneous ultrasonic applications include treatment of gases for precipitation of particles and ultrasonic liquid-level sensing.

Ultrasonics is often used for dental drilling. This requires an ultrasonic generator that supplies energy to a transducer that is also the drilling bit. The shape drilled in the tooth will depend on the shape of the bit. A typical ultrasonic dental drilling bit will vibrate at 30 kHz with an amplitude or range of motion of approximately 0.001 inches. An abrasive is required for drilling and this abrasive is carried in water to prevent dust inhalation by the patient. This method has the advantage of eliminating the usual pain-causing factors in drilling since the ultrasonic drill produces no heat or friction. Also, this drill does not cut soft tissues such as the tongue or cheeks.

Metals such as copper and aluminum form an oxide that prevents solder from making contact with the metal. A solid solder bond can not be made unless the solder makes contact with the metal. Chemical fluxes are used to prevent the
formation of oxide when the metals are heated for soldering, however, no satisfactory chemical flux is available for aluminum.[8] If ultrasound is applied to the molten solder in contact with the metal, cavitation in the solder breaks down the oxide film and allows the solder to reach the pure metal surface forming a good bond. This eliminates the need for flux and the later removal of that flux. The chemicals used for flux removal usually have environmental concerns associated with their use.

2.3 Multiple Document Detection

As described above, the two general approach methods for multiple document detection are contact and non-contact. The “paper contact methods” include measurement of small thickness changes with a “contact foot” or sensing arm that is in contact with the documents as they pass through the document scanner. The “contact foot” is connected to a LVDT or a magnet being sensed by a Hall Effect Sensor allowing for the sensing of changes in thickness of less than 1 micron.[11] The major non-contact method involves sending ultrasound waves through the document stream to determine if multiple documents are present.

The major disadvantage to the “paper contact method” is that anything in contact with moving paper, especially thin or ripped paper, can cause a paper jam. This method requires a calibration with the maximum thickness document
that will be fed through the document transport. Then, whenever a thickness is measured above that calibration value plus a threshold (typically 30%) [1], it is determined to be a multiple document feed. Realistically, this method will only work with one thickness document being scanned at a time. The chance of causing a paper jam can be reduced by using a wheel on the end of the "contact foot"; however, the changing diameter of this wheel, due to the nonconformities in manufacturing, must be taken into account during the measurements, greatly complicating the controller.[11]

Ultrasonics can be used as a non-contact method. Sending ultrasound through paper yields two different pieces of data that can be used to determine the presence of multiple document feeds. The first is the attenuation of the signal and the second is the phase shift of the signal. Through the use of an algorithm that uses these data, it is possible to determine the presence of multiple document feeds independent of the thickness of the documents and without making contact with these documents.

An example of the "paper contact method" is in the Eastman Kodak Microimager 70 document scanner. Bell & Howell use a non-contact, "attenuation only method" in their 8080 document scanner. The Eastman Kodak Company document scanner is able to detect 94.4% of the test multiple documents (documents which have been taped together to insure a multiple document is fed into the document scanner). The Bell & Howell is only able to detect 86.3%
of these same test multiple documents.[12] This would indicate that the attenuation method alone is not sufficient for multiple document detection.

Eastman Kodak Company patented the use of the phase shift of ultrasound passing through documents to detect multiple document feeds in 1976. This patent has since run out without being utilized by Eastman Kodak Company. The results of a recent patent search indicate there have been no applications in which both the phase shift and the attenuation are used. Through the use of both of these pieces of data, it is possible to make a decision in that area where the single methods have difficulty making clear-cut decisions.

Ultrasonics has been used for detecting the presence, distance or thickness of paper or other materials and not the occurrence of multiple documents.[13] through [33] Some thickness measurement applications include pipe wall thickness. Based on the literature reviewed, patent searches[34] and technical searches, [35] through [38] this application and approach appears to be unique and clearly offers advantages over all the other methods reviewed.
3 DESCRIPTION OF SYSTEM

The "ultrasonic document detector circuit" is required to transmit, receive and process a 40 kHz ultrasonic sound wave to determine if one or more documents are present. The amplitude of the received signal is used to determine if any documents are present. Once it is determined that there is at least one document present, it must be determined if a multiple document feed has taken place from the amplitude and phase differences of the transmitted and received ultrasonic signals. If more than one document is determined to be present, the host computer is informed of the multiple document feed condition.

The host computer will take the appropriate action when a multiple document feed is detected. This action can include stopping the document transport to allow the user to remove and rescan the document and/or sounding an alarm to inform the user of this condition. The action taken by the host computer is determined by the parameters set by the user through the user interface and is not under the direct control of "ultrasonic document detector circuit". The approaches taken to perform the multiple document detection function are shown in the block diagrams in Figures 1 and 2 and will be described in detail.

3.1 Received Signal Conditioning

The signal at the output of the ultrasonic receiver varies between 1 volt (RMS) and a few millivolts (RMS) depending on the type of paper and the number of
sheets as will be discussed in Chapter 4. With the introduction of a single sheet of paper between the ultrasonic transmitter and ultrasonic receiver, this signal drops below 100 millivolts (RMS) and then this level must be measured to within a few millivolts DC for use by the decision algorithm within the microcontroller. Therefore, the requirements for the signal processing of this signal are very critical. Referring to the block diagram in Figures 1 and 2, the sections that comprise the received signal conditioning are the ultrasonic receiver, the low pass filter, the amplifier, the amplitude detector, the conditioning amplifier and the sinewave to TTL converter.

3.1.1 Receiver, Low Pass Filter and Amplifier

The ultrasonic receiver and amplifier are shown in the block diagram in Figure 1. The amplifier is comprised of a low pass filter/buffer with unity gain to reduce the high frequency noise on the received signal. This signal is then routed into the amplitude detector and the sinewave to TTL squarewave converter.

The low pass filter is a first order filter providing 6dB of attenuation per octave with a cutoff frequency of approximately 106 kHz.[39] During testing, most of the noise was much greater than 1 MHz and, therefore, by setting the cutoff frequency at 106 kHz, the received signal is not degraded while the noise level
is attenuated with a first order filter. The equations for this filter are shown on schematic E-4.

Common mode noise rejection can be improved with an instrumentation amplifier and this was investigated for the “ultrasonic document detector circuit”. This approach requires that the signal from the ultrasonic receiver was not grounded on one side and this results in a more complex design with no clear advantages. Experimentation with the instrumentation amplifier approach and the method implemented proved the instrumentation amplifier is not needed.

3.1.2 Amplitude Peak Detector

The amplitude peak detector is a critical circuit within the “ultrasonic document detector circuit” and required substantial development time. Ideally this peak detector would present a DC level indicating the exact value of the applied peaks which would be updated with every signal cycle and there would be no offset from the peak value of the previous cycle. If the peak hold time constant is too short, the conditioned signal from this circuit will have a large AC component on the peak level. This will result in the amplitude level at the input to the A/D converter varying randomly since the A/D converter sample time is asynchronous to the received ultrasonic signal resulting in errors in the
measured amplitude level. If the time constant is too long, then some multiple document feeds will be missed. These multiple document feeds result in lower amplitudes and their duration may be shorter than this time constant in the situation where the documents are only partially overlapping.

The amplitude peak detector is required to work over a large input dynamic range with input peak levels as small as a few millivolts and as large as 10 volts. A few millivolts offset would be a small percentage of the total level if the input was 10 volts and would not cause a problem in the "ultrasonic document detector circuit". However, if these same few millivolts of offset were introduced when the input was also few millivolts, the error could be larger than the signal of interest with the result the actual signal level would be difficult to determine.

Three methods of peak amplitude detection were explored for the "ultrasonic document detector circuit". The first method is the traditional approach, which uses a diode to pass the positive levels of the signal to a RC circuit that holds these peak values. The time constant of the RC circuit is determined by the values of the resistor and capacitor and the selection of the time constant is based on the frequency applied. This method has the disadvantage of only being able to detect signals larger than the forward voltage drop of the peak detection diode and it has a negative offset error equal to this diode drop. Although this method is simple and cheap to implement it was eliminated since it
will not work with the small signal levels processed by the "ultrasonic document detector circuit".

The second method uses a precision rectifier that is implemented with an op amp circuit that has a diode in the feedback path. This op amp circuit enables the peak level of the applied signal to be taken without a forward diode drop offset error being introduced as would normally be experienced with the traditional peak detector discussed above. This circuit has feedback only for positive output signals and these positive signals are applied to the peak holding capacitor. When the output signal goes negative, the diode is reverse biased and no feedback is provided.[41] However, this allows the output to swing to the negative supply rail since there is no feedback with negative outputs. This method of peak detection also reduces the loading on the previous stage by the buffering effect of the op amp. The RC time constant for this method is determined the same way as it was for the traditional peak detector circuit. Since the precision rectifier method works with no diode voltage drop, it could be used for the "ultrasonic document detector circuit".

The third method uses a precision full wave rectifier as an input to the precision rectifier and this has the advantage of applying both the negative and positive peaks to the peak holding capacitor. Since the signal from the ultrasonic receiver is a symmetrical sinewave, both the positive and the negative peaks are the same absolute amplitude. This method is implemented in the final
design because it allows the time constant of the peak holding circuit to be cut in half since the capacitor is charged twice on each sinewave cycle. This reduction in the time constant allows the response of the peak detector to be twice as fast at it would be with just the precision rectifier alone. This results in the "ultrasonic document detector circuit" being able to respond to the presence of multiple documents twice as fast. Since this time constant was determined to be the bottleneck for processing time during development, the additional complexity of this circuitry is justified to increase the overall performance.

The peak holding capacitor was connected directly to the output of the precision full wave rectifier in the initial design of this section. This provided a discharge path from the peak holding capacitor through the two feedback resistors in the precision full wave rectifier, as in schematic E-4. Since the resistor in the non inverting amplifier circuit within the precision full wave rectifier is not connected to a virtual ground, the current flow from the peak holding capacitor through this resistor is dependant on the input voltage applied to the precision full wave rectifier. This results in the time constant on the peak holding capacitor being dependent on this applied voltage. A precision peak detector is included at the output of the precision full wave rectifier to correct this problem by eliminating this discharge path, as in schematic E-4.

The precision peak detector implemented actually uses two diodes in the feedback path, as in schematic E-4. The diode, with its anode connected to the
output of the op amp, is used to provide the required offset for the diode drop, as just discussed. The second diode, with its cathode connected to the output of the op amp, reduces the negative swing at the output of this op amp by providing feedback when the op amp output swings negative. This prevents the output stage of the op amp from becoming saturated with negative outputs and, thereby, speeds the operation of the op amp by eliminating the time required to pull the output stage out of saturation.

The output of the precision peak detector is applied to the holding capacitor through a series resistor and three diodes connected in parallel. The series resistor limits the current from the output of the op amp. The three diodes in parallel reduce the forward drop across these diodes as the current through them increases. Ideally, the voltage drop across these three parallel diodes would be the same as the feedback diode. However, a large amount of current must flow through these parallel diodes to charge the peak holding capacitor and this current will increase with larger signals. The parallel diodes reduce this voltage drop difference between the feedback and output diodes and, thereby, reduce the offset at the output of the precision peak detector. More diodes could be paralleled or matched diodes could be used to future reduce this effect. A buffer is used at the output of the precision peak detector to prevent loading from discharging the peak holding capacitor.
During the development of the precision peak detector the circuit was extensively simulated with SPICE. These SPICE input text files and the output waveforms can be found in Appendix E. The output files include simulation results for both large and small peak detection as can be seen in E-1 and E-2 respectively.

3.1.3 Conditioning Amplifier

The conditioning amplifier is needed to improve the dynamic range of the received signal at lower voltage levels. With the introduction of a single sheet of paper, testing shows the received signal falls to less than 1/100th of the peak value without paper and it is the voltage levels with paper present that must be measured. Therefore, the voltages of approximately the lowest 1% of the full range of the received signal will contain the data of interest. Among the methods to improve the sensitivity in the range of interest are: adding more bits on the A/D converter, using a log amplifier, and using two or more different amplifiers with different gains being processed by separate A/D converters inputs.

Given a signal that has a maximum level of 10 volts peak and an 8-Bit A/D converter, the resolution is approximately 39 millivolts DC. If a 12-Bit A/D converter is used, the resolution is approximately 2.4 millivolts DC and if a 16-Bit
A/D converter is used the resolution is approximately 153 microvolts. A resolution of approximately 2 to 3 millivolts DC is required so both the 12-Bit and the 16-Bit A/D converter would provide the required resolution. There is a one LSB Bit change for a 2.4 millivolts DC change with a 12-Bit A/D converter and a four LSB Bit change for a 16-Bit A/D converter.

A log amplifier can be implemented through the use of the logarithmic characteristics of a diode in an op amp circuit by either building this circuit with discrete electronic components[42][43] or through the use of an IC with this functionality. Temperature compensation is required for the resolution needed for the “ultrasonic document detector circuit” and many of the log amplifier ICs have internal temperature compensation, making the IC log amplifier a better choice. A log amplifier increases resolution at lower input levels at the expense of resolution at higher input levels and the resolution is more critical at low levels in this application. For analysis, if this log amplifier is set up so that 10 volts applied results in 10 volts out, there is 0.625 volts out of this amplifier with 1 millivolt DC applied. If this level is applied to an 8-Bit A/D converter, the value out of the A/D converter is 16-bits with 1millivolt DC applied with the result that the resolution is approximately 625 microvolts at the 1millivolt DC level. This approach provides the resolution required for the “ultrasonic document detector circuit".
The third method is shown in Figure 7. This method uses the unamplified peak signal for one of the inputs to the A/D converter and has another input being driven by an amplified version of the input signal. If the gain of the amplifier is 100, then for an applied level of 100 millivolts DC, the output is 10 volts DC or the full range of the A/D converter used. If an 8-Bit A/D converter is used, the resolution is 390 microvolts per bit. This method could easily be adjusted for higher or lower gains to obtain the resolution needed. As shown in Figure 8 and schematic E-4, the approach taken uses the peak level, the peak level amplified by 11 and the peak level amplified by 121. These three levels are connected to three A/D converter inputs on microcontroller. The gains were selected to be approximately 10 for each stage and since the microcontroller had extra inputs on the A/D converter, the output from the center gain stage is also used. The inputs to the two amplifier stages are clamped with diodes to prevent the op amp outputs from going into saturation so that the response time of these op amps is not reduced. All three of these inputs are clamped using zener diodes to prevent the A/D converter inputs from reaching a voltage greater than the high reference on the A/D converter, as in schematic E-4. This prevents the A/D converter from being damaged.
Figure 7 First Method to Increase Dynamic Range of A/D Converter
Figure 8 Second Method to Increase Dynamic Range of A/D Converter

As with all choices, there are advantages and disadvantages to each method. The high bit resolution A/D converters cost more, are slower, require cleaner power supplies and require processing larger numbers in the microcontroller.\[44\] Cleaner power supplies increase the cost, and greater than 8-bit math within an 8-bit microcontroller slows the processing time and complicates the firmware.\[45\] The log amplifier adds some complication in setting up the gains to obtain the full range, the decision algorithm within the microcontroller is more complex, there is additional cost and circuit complexity and the resolution at the lower levels comes at the expense of the resolution at
higher signal levels. The third method is low cost and straightforward to design however, it does require clamping of the signal at the input of the high gain stage to prevent saturation of the op amp. The third method is used since it is the lowest cost and the easiest to implement while providing the required resolution.

3.1.4 Sinewave to TTL Converter

The conditioned received signal is a sinewave varying between a 10 volts (RMS) and a few millivolts (RMS). This signal needs to be a TTL level to interface to the phase comparator that is within the EPLD. If there is any phase shift from the input to the output of this section, it will limit the range over which the Phase Comparator can be used, as will be explained in the following section. This sinewave to TTL level conversion is accomplished through the use of a comparator that has its negative input connected to ground to form a zero crossover detector. This comparator must have a low DC offset since the applied signal can be a few millivolts and any DC offset will result in a phase shift by incorrectly detecting the zero crossover point. This comparator must also be fast enough that little or no phase errors, caused by incorrectly interpreting the time of the zero crossover, are introduced. The DC offset can cause either a positive or a negative phase error whereas the slow response would result only in a positive phase error.
Any phase errors will limit the usable dynamic range of the phase detector. The test bench results shown in Table 4-2 indicates a phase shift of 115-degrees for a picture and 144-degrees for two pink receipts when the distance is 0.440" between the ultrasonic transmitter and ultrasonic receiver. If the total phase error due to all sources was a positive 29-degrees, then a single picture being scanned could incorrectly be interrupted as double pink receipts. If the total phase error was a negative 29-degrees, then double pink receipts scanned together as a multiple document feed could incorrectly be interpreted as a single picture with the results that the multiple document feed was not detected. Therefore, all phase errors combined must be less than 29-degrees if both of these document types are to be included among the documents to be scanned.

The phase error situation is even more critical when the distance between the ultrasonic transmitter and ultrasonic receiver is reduced to 0.132", as in Table 4-1. A single photograph generates 152.6-degrees of phase shift while two pieces of cardboard only 139.6-degrees. The phase shift for a single photograph is less than for two pieces of cardboard. Clearly this situation causes difficulty detecting multiple document feeds with this small a distance between the ultrasonic transmitter and ultrasonic receiver. This is not a problem in the "ultrasonic document detector circuit" since the distance used is larger than the 0.132" distance for the data in Table 4-1. Also, thicker documents such as
photographs and cardboard rarely multi feed.[1] Additional details will be discussed in the test bench section in Chapter 4.

The original approach for the design of this section does not connect either side of the ultrasonic receiver directly to ground. Instead, it uses a low pass filter applied to the negative input terminal of the comparator to extract the DC offset value from the received signal. In testing, this method was found to be susceptible to noise. When there was noise introduced into this section and the received level was small, the low pass filter would shift to a level higher or lower than the peaks in the received signal preventing the comparator output from switching until this DC offset bled off the capacitor. This problem is resolved by connecting one side of the ultrasonic receiver to ground and the negative input of the comparator to ground.

Since the conditioned signal received can be as high as 10 volts peak-to-peak, the DC power supplies used for the comparator needed to be larger than +/- 10 Volts DC to prevent latch up. This results in the need for a level shift and reduction in the output level to TTL compatible levels. The level shift function is performed internal to the comparator, as in schematic E-4.
3.2 Drive Signal Section

The transmitter must be driven with the required frequency signal at the proper voltage level to insure enough ultrasonic energy is sent to the detector. The ultrasonic transmitter is a resonant piezoelectric crystal and, therefore, can be driven with a squarewave without introducing any harmonics in the signal it produces. This driving signal must be of the proper amplitude and frequency to produce the required output level. In addition, this level and frequency is adjusted as described in the section on calibration. Referring to the block diagram in Figure 1, the sections which comprise the Drive Signal Section are the Volt to Frequency (V to F) Converter, the Driver and the 180-degree Phase shift sections.

3.2.1 Voltage-To-Frequency Converter

Voltage to frequency conversion can easily be accomplished with any of several commercially available ICs. A common method to perform voltage-to-frequency conversion uses a Phase Locked Loop (PLL) and is based on RC time constants. The output frequency is proportional to the applied voltage.[46] The use of resistors and capacitors to generate a reference frequency introduces a limitation into this process as the actual values of these components are temperature dependent. A calibration process compensates for device tolerances before use, however it is not able to compensate for temperature
changes during operation unless the calibration is preformed dynamically. Performing a fine resolution calibration during the interdocument gap period is one solution. This would result in a continuous or dynamic calibration that would compensate for the drift due to temperature. It was found during testing that the internal temperature of a document scanner could change as much as 40-degrees Fahrenheit within several minutes clearly indicating the need for using a dynamic calibration if this approach were used.

The temperature testing was performed by placing several thermocouples inside the document scanner in the areas where both the electronic circuitry and the ultrasonic transmitter and ultrasonic receiver would be placed. The document scanner was allowed to reach temperature equilibrium while in a standby mode and this temperature was used as the reference temperature. Documents were then fed through the document scanner and the temperature changes were observed. The internal temperatures were found to drop approximately 40-degrees Fahrenheit within a few minutes of the time the documents were fed and then the temperature leveled off. There is almost no reduction in the power consumed by this document scanner in the standby mode resulting in approximately the same amount of heat being introduced to the interior in both the run and standby modes. However, when the document scanner is transporting documents, there is air turbulence as these documents pass through the transport and these documents are also at room temperature which
is lower than the interior temperature of the document scanner. This causes a cooling effect inside the document scanner and a heating of the documents.

### 3.2.2 Sensor Driver

The sensor driver provides the required current and voltage to the piezoelectric ultrasonic transmitter. The ultrasonic transmitter voltage is a nominal 24 volts DC, which is higher than a TTL device can provide with the ultrasonic emitter used in the "ultrasonic document detector circuit". Additional headroom was designed into the Sensor Driver so that alternate ultrasonic transmitters could be used that might require higher currents and/or higher voltages. A maximum voltage of 150 volts DC at 200 milliamps can be delivered by the transistors selected.[47] This section also needs to have an adjustable driving voltage level to be used for the amplitude calibration process. By increasing the drive level instead of increasing the gain on the received signal, the signal to noise ratio does not decrease in the "ultrasonic document detector circuit". This can be seen on schematic E-6.

### 3.2.3 180-degree Phase shift

A 180-degree phase shift of the received ultrasonic signal is required to enable the phase detector to have as much of its 360-degree range for use as possible.
This is a coarse adjustment to provide a starting point before the fine phase adjustment. If a phase adjustment is not provided, then the phase detector does not have the required dynamic range to detect multiple document feeds. For example, if there is a 180-degree phase shift with no documents present, the phase detector will indicate a 0-degree phase shift with two documents present if each document introduced 90-degree phase shift.

3.3 Firmware, Digital and Control Circuitry

The "ultrasonic document detector circuit" is a mixture of analog and digital circuitry. The digital circuitry is comprised of an EPLD that performs the phase detection algorithm and clock generation, a microcontroller that performs the decision algorithm, and some interfacing digital circuitry. All of the electronic components selected for the "ultrasonic document detector circuit" were available from more than manufacture except for the microcontroller and the EPLD.

Selection of Motorola for the microcontroller and Altera for the EPLD resulted in a design that would have to be changed if either of these parts were discontinued. This decision carries some long-term risk due to selecting parts only available from one source, however both of these manufactures have an excellent reputation for having an upgrade path for any parts that they discontinue.[44] Generic parts were investigated such as a 68000
microprocessor instead of the M68HC711E9 microcontroller and 22V10 PALs instead of the EPM7128 EPLD selected. Since this would have resulted in a more complex design by requiring additional parts (ROM and RAM external to the 68000, an A/D and more than one 22V10) and additional expense, the M68HC711E9 microcontroller EPM7128 EPLD were selected.

To reduce the time to reengineer the design in the event that either of these parts became unavailable, VHDL is used for the EPLD and ‘C’ is used for the microcontroller. Alternatives investigated included AHDL for the EPLD and assembly for the microcontroller. Both of these were eliminated in favor of the more generic languages selected. Both the VHDL code and the ‘C’ code was written with as few vendor specific requirements as possible resulting in code that is more transportable to another vendor.

3.3.1 Microcontroller

The microcontroller used in the “ultrasonic document detector circuit” is a Motorola M68HC711E9. This microcontroller has an 8-Bit core with an internal bus speed of 2 MHz. The internal clock is derived from an external 8 MHz oscillator that is divided internal to the microcontroller. The higher speed oscillator is divided to ensure the clock phases are symmetrical and so that a multiple phase clock is available for use internal to this microcontroller. The fully
static design of this microcontroller allows operation at frequencies down to DC to reduce power consumption. The bus speed is maintained at a constant 2 MHz in this application because power consumption is not a concern.

The power consumed by this microcontroller is very small compared to full power utilized by a document scanner. Power consumption is more critical in battery powered applications, however, it is becoming a concern due to the lower power requirements in many market places, especially the European Markets. Combining small power reduction opportunities, such as reducing the power consumed by the microcontrollers throughout a full system, will add up significantly. An electronic device such as a document scanner often has power turned on but is not actually scanning documents and during these times there exists many power savings opportunities.

Internal to the Motorola M68HC711E9 microcontroller are the following subsystems: 12K EPROM, 512 EEPROM, 512 RAM, an 8 channel A/D converter with 8-bits of resolution, I/O registers, an interrupt controller, a SPI, a SCI and a 16-bit free running timer. These subsystems are all accessible by the CPU through internal busses. This high level of integration reduces cost, improves reliability, decreases board space and simplifies the electronic circuitry when compared to a design that uses individual ICs for these subsystems. The time required to complete the design is also reduced.
The internal EPROM is used for storage of the executable code of the program that is run on this microcontroller. This microcontroller is an OTP device, therefore, if there is the need for a code change the previously programmed microcontroller must be discarded and a new one must be programmed with the new code in much the same way programming a new PROM is done with a microprocessor. A version of this microcontroller that has UV erasable ROM was used for code development. Using the OTP microcontrollers for code development would have required that a new microcontroller be used for each code change. Programming of the microcontrollers is done before it is installed on the socket on the PCB. The EEPROM is used for storage of variables that need to be changed during code execution and that need to be saved when the document scanner is powered down. Examples of these types of variables are the calibration data. By maintaining the calibration data in this nonvolatile EEPROM, the need to perform a calibration after cycling the power on the document scanner is eliminated. The EEPROM can only be changed or reprogrammed approximately 10,000 times and therefore it can not be used for variables that change frequently. The RAM is used by the microcontroller for both variables that do not need to be nonvolatile and the stack. All three of these memory types have the same access time so there is no speed advantage by using one type of memory over another.

The A/D converter internal to this microcontroller is an 8-channel, 8-bit successive-approximation converter with +/- ½ LSB accuracy over the complete
operating temperature range specified by Motorola. It uses an all-capacitive change-redistribution technique for conversions. The high and low voltage references for this A/D converter are separate from the VDD and ground pins to this microcontroller, which would allow voltages other than 5 volts DC to be used.[48] For the “ultrasonic document detector circuit” 5 volts DC was used for the high voltage reference and ground for the low voltage reference for the A/D converter. These signals were filtered with capacitors placed in close proximity to the input pins, as in schematic E-5. Noise at these reference voltage pins effectively reduces the resolution of the A/D converter. For example, 156 millivolts of noise corresponds to the three LSBs of the A/D converter and this would reduce the 8-Bit A/D converter to effectively only 5-Bits of resolution.

The I/Os in this microcontroller are used for interfacing to the digital circuitry on the “ultrasonic document detector circuit” and to the host computer, as in schematic E-5. Since there is no memory external to this microcontroller, none of the I/Os are used for address or data lines. These I/O receive information from the host computer to enable the multiple document feed detection mode and features. These I/O also inform the host computer when a multiple document is detected and when a document is present, as in schematic E-5.

The free-running timer is used to control the time interval for sampling the signal from the ultrasonic receiver. Since this timer is free-running, the microcontroller is not required to perform a delay loop for timing purposes. This frees the
microcontroller up to handle other functions during this time, requiring a less powerful microcontroller. The interrupt controller, SPI and SCI are not used in this application other than for debug.

This microcontroller selected offers many advantages for this application, including low cost and sufficient computing power to process the information required by the decision algorithm.[42] The integration of the required peripherals simplifies the hardware and this microcontroller has enough internal RAM for both variables and the stack allowing the code to be written in 'C'.

3.3.2 Firmware and Decision Algorithm

The firmware for a microcontroller is often written in assembly language to both increase the speed of code execution and to reduce the memory space required for the code. Many simple microcontrollers do not have enough internal RAM to support the stack and the large number of variables used by a higher level language such as 'C'.[11] The complexity of the decision algorithm used for the "ultrasonic document detector circuit" and the large number of subfunctions handled by the microcontroller, such as A/D conversion and software debouncing, made implementation in assembly language extremely complex. In addition, 'C' code is considered more maintainable and is self-documenting, if properly written.[45] Most optimizing compilers provide code from a higher level
language that is almost as fast and space efficient as well written assembler code.[45] The compiler used was Whitesmiths 68HC11 C Compiler/Assembler.

An emulator often simplifies the firmware debug and testing phase by allowing the firmware to be single stepped while verifying proper operation. Break points can be used within the firmware to perform additional testing and verification. An emulator was not used for the “ultrasonic document detector circuit” microcontroller since one was not available. Instead, a serial communication port was added to the microcontroller, as in schematic E-5. This serial communication port is only used for debug and firmware testing. This port allows messages and data to be monitored on a terminal while the firmware is executing in the microcontroller. Although this was not the best solution for firmware debug, it is a method to test the firmware without the cost of the emulator.

The main function the microcontroller performs, other than calibration, is the determination of the presence of multiple document feeds. The decision algorithm for this function is shown in Figure 9 and the source code used by the microcontroller is in Appendix B.

In this decision algorithm, the microcontroller starts by checking the amplitude of the received ultrasonic signal to determine if any paper is present in the ultrasound path. If paper is present, the algorithm first compares the amplitude
level to determine if there is a multiple document feed condition by comparing the received signal level against a constant. If the received signal level is below this constant, then the ultrasonic signal has been attenuated by the presence of multiple documents. The amplitude multiple document feed counter is then incremented and tested to determine if the debouncing conditions have been met. If the debouncing conditions have been met, the host computer is interrupted to indicate a debounced multiple document feed has been detected. If the debouncing conditions are not met, the algorithm will test for the presence of indicated phase multiple document feed detection.

If the amplitude of the received signal is above this constant, then the conditions have not been met for the determination of a multiple document feed and the amplitude multiple document feed counter is then decremented as part of the debouncing process. This decision algorithm then tests the phase difference between the signal to the ultrasonic transmitter and from the ultrasonic receiver to determine if the phase method indicates a multiple document feed condition. The debouncing method for the phase detection method is the same as for the amplitude detection method.
Figure 9 Firmware Decision Algorithm
3.3.3 Debouncing to Reduce False Multiple Document Detects

The methods used in the "ultrasonic document detector circuit" will incorrectly indicate the presence of multiple document feeds in certain situations, such as when there is a staple in the document, an edge of the document is folded over or when there is a label or sticker on the document, if they are not addressed. Clearly these are not multiple document feeds and these situations must be accounted for. Also, noise introduced into the system could possibly incorrectly indicate the presence of multiple document feeds for one or two samples. These situations are addressed by a debouncing scheme that requires the indicated presence of a multiple document feed for approximately one inch of document travel before a known multiple document feed is reported to the host computer.

This debouncing is accomplished within the microcontroller through the use of a counter that requires $\frac{1}{2}$ the samples within a sampling window to indicate the presence of multiple documents. This window is under the control of the user since a longer window size is needed in certain situations, such as the presence of stickers or labels on the documents being scanned. By increasing this window size, these stickers or labels will not falsely indicate a multiple document feed.
Approximately 100 samples per inch are taken of the document as it passes through the document transport. With the detection window size set to one inch there must be 100 samples indicating a multiple document feed in a window size of 200. This is accomplished by setting a counter that can only count between 0 and 100. For each indicated multiple document feed, one is added to this counter. For each indicated single document feed, one is subtracted from this counter. Whenever the counter reaches 100, the microcontroller determines a debounced multiple document feed has been detected and the host computer is interrupted to inform it of this situation.

Two methods can be used to determine the document length to average the one inch window for the 100 samples. The first method samples the document at fixed time intervals. This method only works for a single document transport speed, however it is the easier method to implement. The second method uses pulses from the document transport stepper motor drive circuit to determine the document transport speed. This method works for all document transport speeds, however it is more complicated to implement. The second method is the one in use in the “ultrasonic document detector circuit”, since it provides the maximum flexibility.

This approach to debouncing results in a method that can easily be implemented within the firmware and has the flexibility to be adjusted for different window sizes for specific applications that might arise in the future.
3.3.4 EPLD Function, Design and Simulation

An Altera EPM7128S-15 EPLD is used to implement the programmable logic for the "ultrasonic document detector circuit". This device offers the required density and speed needed for this design at a low cost while allowing the flexibility for possible required design changes or modifications. If additional space for programmable logic is required, there is a direct upgrade path that is both code and pin-for-pin compatible to the Altera EPM7160 series that would provide the internal circuitry for 25% more logic. The slowest speed Altera EPM7128S EPLD is used in the "ultrasonic document detector circuit". Altera has pin-for-pin compatible devices available in faster speed grades, at a higher cost, if additional circuit performance is needed.

The Altera Max 7000 Series EPLDs are CMOS EEPROM-based programmable logic devices that offer operating speeds up to 178.6 MHz and pin-to-pin logic delays as small as 5-ns. The 7000 Series EPLDs are available with 600 to 5,000 usable gates and come in package sizes of 44 to 208 pins. The Max 7000 series EPLD architecture is comprised of Logic Array Blocks, Macrocells, Expander Product Terms, Programmable Interconnect Arrays and I/O controller Blocks. The Logic Array Blocks consist of 16 Macrocell arrays. The Macrocells are used to implement combinatorial logic and registers. The Expander Product Terms are used to interconnect the Macrocells when a function can not be implemented in a single Macrocell. The Programmable Interconnect Array is
used to route the logic signals within the EPLD. The I/O Control Blocks allow each I/O pin to be individually configured as input, output or bi-directional operation. These devices are especially efficient at implementing state machines and counters.[49] For additional details on the Altera Max 7000 Series EPLDs see the Altera Data Book as listed in the references.

The Altera EPM7128S-15 EPLD used for the “ultrasonic document detector circuit” has 2500 usable gates and is the 15-ns speed grade device. The utilization of the internal circuitry of this device is approximately 40%, which allows room for design changes and addition of future functions. An EPLD with less internal circuitry could have been selected for a small reduction in cost, however, this may have precluded any future changes that might be needed. If changes were needed and there was not enough internal room within the EPLD, it would require rework of the PCB to implement them. The MaxPlus timing analyzer indicated the design operates at a maximum clock speed of approximately 45 MHz. With a system clock speed of 16 MHz in the "ultrasonic document detector circuit" there is the performance headroom within this EPLD to increase the clock speed, if additional performance is required.

The major digital logic functions preformed by the Altera EPM7128S-15 EPLD are phase difference measurement algorithm, clock generation for the ultrasonic transmitter and clock generation for the microcontroller. The EPLD design is written in VHDL and the source code is in Appendix C. This VHDL code was
compiled and simulated on Altera's MaxPlus compiler. The speed analysis for the EPLD was also preformed on MaxPlus with the previously mentioned results. The simulation results are shown in the waveforms in Appendix D. All of these waveforms are of the same simulation with different time scales to show the detail of the operation of the state machine. The clock functions are also shown. Additional simulation was conducted to insure proper operation, however, complete results were not included due to the size of these results. Figure 10 shows the state machine implementation of the algorithm used for the phase difference measurement.
The phase difference state machine waits in the "Update Phase Measurement State" until the reference (ultrasonic drive signal) goes low. Upon detection of this low going edge, the phase difference counter is initialized and the phase
difference measurement is ready to start. The state machine waits in the "Counter Initialization State" until the reference signal goes high resulting in the phase difference counter starting. If the sample signal is high, the state machine goes to the "Counting Phase Difference A State". If the sample signal is low, the state machine goes to the "Counting Phase Difference B State".

The phase difference counter continues to count on each system clock while in the "Counting Phase Difference A and B States" until the sample signal (signal from the ultrasonic receiver) changes state. This state change results in a measurement of the time from the reference signal going high to the sample signal changing state. If the state machine is in the "Counting Phase Difference A State", the phase difference measurement is complete and the state machine moves to the "Update Phase Measurement State". If the state machine is in the "Counting Phase Difference B State", the state machine moves to the "Counting Phase Difference C State" to complete phase difference measurement for the period while the sample signal is low.

3.4 Electronic Component Selection and Schematic Design

The selection of the microcontroller and EPLD were based on cost and performance reasons discussed in their respective sections above. The passive electronic components were selected based on circuit requirements, power
dissipation and cost. The active components used for the analog processing required additional consideration during the selection process.

The analog signal from the ultrasonic receiver is converted to a TTL level through the use of a comparator, as in schematic E-4. Ideally, this comparator would have no propagation delay and no DC offset voltage, since both of these conditions contribute to phase difference errors. The propagation delay introduces a positive phase difference error, whereas the DC offset introduces both positive and negative phase errors, depending on the direction of the received signal. The calibration process within the microcontroller can compensate for the positive phase difference error from the propagation delay. However, the error from the input offset can not be compensated for since it causes errors in both directions. The amount of propagation delay and input offset are temperature dependent, resulting in system performance changes as the temperature changes. Clearly, the smaller these errors, the better the overall performance of the "ultrasonic document detector circuit".

The comparator selected is an Analog Devices AD790. This part is more expensive than a typical low cost comparator, such as an LM339, however it is a much higher performance comparator that reduces the introduction of phase difference errors due to propagation delay and DC offset. In addition, this part allows the "ultrasonic document detector circuit" to work with higher frequency ultrasonic receivers. This comparator has a 45-ns maximum propagation delay
and 250 microvolts maximum input offset, which is lower than typical a comparator.[11] This device has a TTL compatible level interface on the output that simplifies the interfacing of this signal to the EPLD for the phase difference measurements. By increasing the level of integration the reliability of this design is improved and the assembly cost is reduced.[44]

The op amps are used in the "ultrasonic document detector circuit" to process the signal from the ultrasonic receiver. These op amps are used as buffers, amplifiers and an active filter, as in schematic E-4. These op amps are required to handle a 40 kHz signal with output levels as high as +/- 10 volts. The required slew rate is calculated as follows:

\[
\text{Slew Rate} = \frac{\Delta V}{t}
\]

\(\Delta V\) is the output voltage change in volts.

\(t\) is the time in of change of the output in microseconds.

This results in a required slew rate of 0.8 volts/microsecond. However, if this system is to be used with a higher frequency ultrasonic receiver, the slew rate will need to be higher. Ultrasonic receivers that are used for amplitude only multiple document detection are often 220 kHz. This frequency would require a slew rate of approximately 4.2 volts/microsecond. This results in the need for a
high performance op amp if this circuit was to be tested with the higher frequency ultrasonic receivers.

The op amp selected is an Analog Devices OP482. This part is more expensive than a typical op amp, such as a LM324, however it is a high performance part that has a higher frequency range and greater slew rate than is required. In addition, this part will allow the "ultrasonic document detector circuit" to work with higher frequency ultrasonic receivers. This op amp has a 9 volt per microsecond slew rate and a bandwidth of 4 MHz.[50]

The electronic hardware design was performed using ViewLogic Powerview Software on a UNIX based platform. The version of this software used does not have the ability to simulate mixed signal designs. Therefore, simulation was limited to digital simulation on the EPLD and SPICE simulation for the critical analog circuitry. This simulation is discussed in the applicable sections. The schematics shown in appendix F and G were designed using this software.

3.5 Prior Approaches Using Direct Contact

Paper contact methods of multiple document detect were introduced in Chapter 1 and is explained in greater detail here. The first method involves using a movable "contact foot" that contains a magnet. The "contact foot" touches the documents as they pass through the document scanner. On the side of the
document opposite the "contact foot" is a Hall Effect Sensor that provides a voltage related to the strength of the magnetic field acting upon it. A baseline is determined when no documents are present. As documents enter the document scanner and pass under the "contact foot", the magnet is lifted, thereby reducing the strength of the magnetic field at the Hall Effect Sensor. This reduction in the magnetic field results in a reduced voltage from the Hall Effect Sensor. This yields an inverse relationship between document thickness and voltage from the sensor. This voltage is processed through analog circuitry, as in schematic E-4. After the analog processing, this voltage representation of the document thickness is processed by a microcontroller, after being converted to a digital signal by an A/D converter, as in schematic E-5.

The algorithm used by the microcontroller functions by measuring the thickness of a reference document passed under the "contact foot" during a calibration process. This thickness is used as a baseline to compare the documents that are being scanned against. If the indicated thickness of any of the following documents passing under the "contact foot" are above a user-set percentage of the thickness of the calibration document, then a multiple document feed is indicated. The user-set over-thickness range is between 30% and 50%. This is required to allow for drifting within the electronics, the change in the magnet strength due to temperature changes and some tolerance of the actual document thickness for single documents.
The calibration process first involves adjusting the zero point of the signal received from the Hall Effect Sensor by offsetting this signal with an analog voltage from a D/A Converter, as in schematics F-4 and F-5. Once the zero point is set, the gain of the analog system is adjusted using an instrumentation amplifier with a programmable gain. The zero point must be readjusted after setting the gain. This process is repeated since the adjustments are interactive. This calibration process is required to ensure the full dynamic range of the A/D converters is used.

One of the biggest disadvantages to this method is that it is not document-independent. A single document that is thicker than the calibration document plus the user-set over-thickness value will be interpreted as a multiple document feed since this method measures only the actual thickness of the documents. Additional disadvantages mentioned previously include wear of the “contact foot” and increased paper jams due to paper contact by the “contact foot”.

The second “paper contact method” involves the use of a wheel in contact with the documents being scanned that is connected to a LVDT through a pivot arm. The LVDT produces a signal that is related to the thickness of the document and is processed in much the same way as the signal from the Hall Effect Signal and therefore this electronic processing will not be discussed. This technique was developed at Eastman Kodak Company and is in limited use. The ability of this
approach to accurately detect multiple document feeds is much lower than for the Hall Effect Sensor approach and this approach was not continued.[11]

3.6 Reapproach to Design

During the breadboarding and test phase, the Volt to Frequency Converter had drift beyond that which could be tolerated and the Phase Comparator was very susceptible to noise and component placement. Both of these sections simulated correctly but once real world parameters, such as temperature change and noise are taken into account, potential for problems became evident. Since both these sections are key to the central design approach, other methods were investigated.

The Volt to Frequency Converter methods analyzed for the “ultrasonic document detector circuit” involved frequency generation based on resistor and capacitor values and an applied voltage. During the calibration phase, the tolerances of the resistors and capacitors involved would be compensated for. However, during operation the temperature and voltage changes would be much more difficult to deal with. Since the operating temperature is expected to change as much as 40-degrees Fahrenheit in a few minutes, a dynamic calibration process is required and this is not practical for all possible applications of the “ultrasonic document detector circuit”. In addition, a D/A Converter is required to obtain the analog voltage that is to be used to control the Voltage to Frequency Converter.
The Phase Comparator proved to be too susceptible to noise on the input signal and noise introduced through the circuitry in the vicinity of this circuit. The full range of the Phase Comparator is minus 360-degrees to plus 360-degrees for a total of 720-degrees of phase detection. With the introduction of noise into this circuit, the indicated phase shift often shifts 360-degrees. For example, if there is a 300-degree lag and noise is introduced, the indicated phase shift could then indicate a 60-degree lead. This problem most often occurs when there is both noise and an actual phase shift occurring at the same time. Although it would be possible for the decision algorithm within the microcontroller to take this into account and properly interpret the actual phase shift when there is no change in phase due to noise, it would not always be possible to correctly interpret this data. For example, when there is an actual phase shift occurring at the same time there is a noise-induced phase shift, it would be difficult to accurately make this decision. Clearly this possibility for a possible unknown phase shift could not be allowed to remain in the "ultrasonic document detector circuit". It is believed that this problem could be eliminated by proper filter of the incoming signal, loading the ultrasonic receiver with a resistive load, adequate power supply filter and careful layout to this area of the circuit. However, the possible risk was determined to be too large and other possible methods were explored.

The original design approach was predominately analog and digital approaches had not been fully explored. Exploring this problem from a digital approach
resulted in the method shown in Figure 2. Through the use of digital circuitry the voltage to frequency converter, phase comparator and 180-degree phase shift is eliminated. An EPLD contains the digital circuit that implements this new approach. The phase difference measurement is accomplished with a digital timer that measures the time difference between the positive going zero crossover of the driver signal and that of the received signal. Since it is possible to make this measurement digitally without the introduced 360 phase shift (as in the analog case) and since these digital values can be handled easily by the microcontroller, there is no need to calibrate the phase of the received signal with the voltage to frequency converter. The voltage to frequency converter is then eliminated. The 180-degree phase shift is accomplished, when needed, by selecting the negative going zero crossover of the received signal instead of the positive going zero crossover. This is easily accomplished within the Detection State Machine within the EPLD. The D/A is also eliminated which both reduces the cost and complexity and increases the speed of operation.

3.7 Calibration

A calibration process is required to insure the full dynamic range of the 8-channel A/D converter is used and that the received values fall within an acceptable range for the electronics. An electronic calibration or a software calibration is preferred over a mechanical calibration as it will reduce production costs and can take place during normal system operation.
3.7.1 Sources of Errors

Calibration is required to compensate for differences from one system to another and this includes:

-Mechanical Tolerances in production. This value can be approximately +/-0.5mm difference in the separation between the ultrasonic transmitter and ultrasonic receiver.[1] This difference in separation corresponds to approximately a minimum of +/-1-degree up to a maximum of +/-35-degrees of phase shift. The higher value represents the worst case and it is not a situation that will be encountered since the paper is not in this area during scanning. Additional details on phase shift vs. the distance between the ultrasonic transmitter and ultrasonic receiver will be discussed in Chapter 4. It is possible to have these tolerances compensated for through a mechanical calibration during manufacturing, however, in the event of replacement or disassembly of any of the related parts by field service personnel, there would have to be another mechanical calibration performed. This would prove to be difficult and expensive. In addition, any changes in the separation between the ultrasonic transmitter and ultrasonic receiver due to temperature changes would be introduced directly as a phase shift error. Mechanical wear will also result in the need for adjustments after use.
- Ultrasonic transmitter and ultrasonic receiver sensitivity. The actual sound output level from the ultrasonic transmitter for a given input voltage and the voltage output level from the ultrasonic receiver for a given input level sound level varies from device to device. Ultrasonic transmitters and detectors could be screened and matched so that a more sensitive device is matched with a less sensitive device to reduce the effect of random part selection. However, this would be an expensive and time-consuming process.

- Electronic Parts Tolerance. The power supplies and driving components will vary with component batch and temperature. The gains in the ultrasonic receiver section will also vary. Although these tolerances are small, even if they combine in the same direction, the resulting error may be large enough that it needs to be compensated for.

3.7.2 Calibration Process

The introduced errors described in the previous section are corrected with a calibration process that adjusts for both received amplitude differences and phase differences. This process is dynamic, taking place at any point in time when there are no documents present in the ultrasound path. The base values are adjusted only when no document is present as this is the reference point
and it is the changes from this reference point that are used by the decision algorithm within the microcontroller.

The calibration process is detailed in the flow chart in Figure 11. The microcontroller starts the process when no document is present and it insures that no document enters the sensing path during calibration. This can be done by either turning the document transport off through the host computer or by ensuring the amplitude of the received signal never drops below a predetermined level indicating no document has entered the transport. If a document does enter the transport during the calibration process, the calibration is stopped and the calibration values are not updated.
Figure 11 Calibration Process Flow Chart
The calibration process first adjusts the amplitude of the received signal by adjusting the level of the ultrasonic transmitter drive signal. This involves making an adjustment to the drive signal level, allowing time for the system to reach equilibrium and then making additional adjustments as required until the target range is reached. This insures the full dynamic range of the A/D converter is utilized by starting with full range on the input to the A/D converter. The target range is a few bits less than full scale on the A/D converter to guarantee this voltage is not above the high reference voltage of the A/D converter.

Upon obtaining the desired received signal level, the phase is adjusted so there is a 0-degree phase shift indicated at the phase comparator. The Phase Comparator is only able to measure a 360-degree phase shift and any additional phase shift information is lost. For example, if the reference point is a 300-degree phase shift and an additional 100-degrees of phase shift is introduced due to the presence of a document, the Phase Comparator would indicate a phase shift of 40-degrees. This can be taken into account in by the microcontroller, but the Phase Comparator can indicate a negative phase shift when there is actually a positive phase shift since it covers a total of 720-degrees of phase detection (minus 360 to plus 360). During circuit testing, the best results were obtained when the starting point was approximately 0-degrees.
The phase is adjusted first in a coarse, 180-degree stage by reversing the drive signal to the ultrasonic transmitter and then by a fine adjustment by changing the frequency of the driving signal. Since the piezoelectric transmitter and receiver are resonant frequency devices, some signal level is lost when the frequency is varied from that resonant frequency, as in Figure 6. The amplitude needs to be adjusted after this step.

This calibration process takes several iterations for the initial adjustment. After a base line is reached, one or two iterations are sufficient to insure the system is within the allowable range of operation. It is possible to maintain the calibration values in nonvolatile memory within the microcontroller and use these values as the starting point for later calibrations.

The approach of varying the frequency of the ultrasonic transmitter to adjust the phase of the received signal is offers many advantages and is unique to the "ultrasonic document detector circuit".[34] A patent is being pursued for this approach based on this author's work.[51]
4 EXPERIMENTAL PROCEDURE

The general approach take to solve this problem was to research the available information, to analyze the system requirements and then to determine if any data was usable in the work done by others. This information was then used as basis for experimentation on a test bench to develop the method to be used in the design. The results of the research are covered in the literature research section and will not be repeated here. It is worth noting that the approaches used within the "ultrasonic document detector circuit" have not been tried before, resulting in the need for more effort to be put into experimentation than into research to determine the best approach.

4.1 Test Bench Fixture

The test bench setup was comprised of a mechanical fixture, as in Figure 12, which held the ultrasonic transmitter on one support and the ultrasonic receiver on the other support. These two supports could be moved in relation to each other from the point they were touching to the point they were more than one inch apart. The adjustment of this separation was made with a micrometer assembly to allow for accurate measurements of this distance and also insured the distance adjustment was repeatable. The limit of approximately one inch for the separation of the ultrasonic transmitter and ultrasonic receiver was the basis for all of the bench testing since that would be the maximum distance which would be possible to use in actual production of a document scanner. Although
the testing went down to the point the ultrasonic transmitter and ultrasonic receiver were touching, this is not an option since there is the need for documents to pass between these and, therefore, some separation is needed.

![Figure 12 Test Bench Mechanical Fixture](image)

The ultrasonic transmitter was driven by signals between 1 and 16 volts (RMS) since this transmitter was to be driven from common electronics that would have voltages up to 24 volts DC available. The received signal was measured with a Tektronix TDS754A 500 MHz, 2-Gig Sample per second oscilloscope, S/N B011777. This same oscilloscope was used during all the testing to insure any
data taken at a later date was repeatable. The bandwidth filter was set to 20 MHz on this oscilloscope to reduce the indicated noise. Any high frequency noise is removed from the actual design using the low pass filter set for 106 kHz on the input, as in schematic E-4. The amplitude and phase shift measurements were made using the internal functions on the oscilloscope and, therefore, were not open to human interpretation during the test process.

4.1.1 Effects of Document Material on the Ultrasound

The document test set used for this testing contained all the material types that a document scanner might encounter during actual use including: 20# bond, 110# bond, wrinkled 20# bond, cardboard from the back of a note pad, manila folder, photographic picture, pink receipt from a multiform document, onion sheet, bank check and newspaper. The same document test set was used during all the testing to reduce the variability caused by using different documents.

The majority of the material types that a document scanner encounters are either 20# bond or bank checks.[1] The rest of these documents were included to explore the limitations of the "ultrasonic document detector circuit". Of the materials in the document test set, 110# bond, cardboard, manila folders and photographic pictures are unlikely to result in multiple document feeds. This is
because a document feeder tends to better separate documents that are thicker and stiffer during the feeding process.[1]

The results of testing with this document test set is shown for 0.132" and 0.440" distance between the ultrasonic transmitter and ultrasonic receiver is shown in data Tables 4-1 through 4-4. The paper was located approximately 0.075" from the ultrasonic receiver for all this testing. The material of the document within the ultrasound path had an effect on both the phase shift and the amplitude of the received signal. These data tables show that generally the thicker the document, the larger the phase shift and the smaller the amplitude of the received ultrasonic signal. However, a thicker document does not always have a greater phase shift, as in Table 4-1 for 20# bond and 110#. The distance between the ultrasonic transmitter and ultrasonic receiver and the position of the paper within the ultrasound path effects the phase shift.

Typically in a document feeder, thinner documents are more likely to result in multiple document feeds because thinner documents will bend more easily taking the shape of the adjacent documents. This reduction in the space between these documents results in two thin documents being pulled into the document feeder as a single document.[1] Therefore, these thicker documents will not degrade the overall performance of the "ultrasonic document detector circuit" during actual use, even though they result in a larger phase shift and
larger signal loss because they are not likely to result in multiple document feeds.

The testing for Table 4-1 was conducted with a distance of 0.132" from the ultrasonic transmitter to the receiver. The data in this table shows that if this distance was used that the "ultrasonic document detector circuit" would fail to detect the case where two pieces of cardboard were involved in a multiple document feed. However, for reasons previously discussed, the cardboard would not be apt to be involved in multiple document feeds. Therefore, multiple document feeds could be detected using phase shift if the case for cardboard was eliminated.

Table 4-2 shows the same data as in Table 4-1 with a distance of 0.440" from the ultrasonic transmitter to the receiver. There are no phase overlap situations in this data table. Therefore, multiple document feeds could be detected using phase shift for this distance and the detection would be completely document-independent. Table 4-3 is a comparison of the results obtained for Tables 4-1 and 4-2.

The testing for Table 4-4 was conducted with a distance of 0.440" from the ultrasonic transmitter to the receiver. The data in this table shows the relationship between document material and the amplitude of received signal. This data table shows crossover of the received amplitude between one and two
documents throughout the table. Clearly the amplitude of the received signal can not be used for document-independent detection of double document feeds at this distance. However, if there are three documents the amplitude of the received signal can be used for multiple document detection since this level is compared to the single document case and there is a much larger delta.

The data within these four tables shows the clear advantage under these test conditions for using the phase shift for document-independent detection of multiple document feeds involving two documents. With three or more documents, phase wrap around needs to be addressed in the phase measurements. The phase shift always increased when a third document was included, however, the measurements for the phase shift with three documents was not included in these tables. The amplitude always decreased when a third document was included as is shown in table 4-4.

The phase shift method has an advantage for the detection of two documents and the amplitude method has an advantage for the detection of three or more documents. The "ultrasonic document detector circuit" was developed to take advantage of this fact. Since the case of three documents or more could easily be detected with the amplitude method, the majority of the development time was spent on the detection of two documents. In addition, the majority of the multiple document feeds are two documents[1] further reducing the need to optimize for the case of three or more documents.
<table>
<thead>
<tr>
<th>Material</th>
<th>Phase Shift w/ 1 document</th>
<th>Phase Shift w/ 2 documents</th>
<th>Delta from 1 to 2 documents</th>
</tr>
</thead>
<tbody>
<tr>
<td>20# Bond</td>
<td>96.1</td>
<td>256.6</td>
<td>160.5</td>
</tr>
<tr>
<td>110# Bond</td>
<td>82.6</td>
<td>230.6</td>
<td>148</td>
</tr>
<tr>
<td>Wrinkled 20# Bond</td>
<td>137.6</td>
<td>214.6</td>
<td>77</td>
</tr>
<tr>
<td>Cardboard</td>
<td>101.6</td>
<td>139.6</td>
<td>38</td>
</tr>
<tr>
<td>Manila Folder</td>
<td>112.6</td>
<td>371.6</td>
<td>259</td>
</tr>
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<td>Photograph</td>
<td>152.6</td>
<td>Note 1</td>
<td>Note 1</td>
</tr>
<tr>
<td>Pink Receipt</td>
<td>116.4</td>
<td>170.6</td>
<td>54.2</td>
</tr>
<tr>
<td>Onion Sheet</td>
<td>89.6</td>
<td>190.6</td>
<td>101</td>
</tr>
<tr>
<td>Bank Check</td>
<td>138.2</td>
<td>185.6</td>
<td>47.4</td>
</tr>
<tr>
<td>Newspaper</td>
<td>81.4</td>
<td>261.6</td>
<td>180.2</td>
</tr>
</tbody>
</table>

Table 4-1 Material Effects on Phase Shift, 0.132” Transmitter to Receiver
Note 1 – Test not conducted with 2 photographs.
<table>
<thead>
<tr>
<th>Material</th>
<th>Phase Shift w/ 1 document</th>
<th>Phase Shift w/ 2 documents</th>
<th>Delta from 1 to 2 documents</th>
</tr>
</thead>
<tbody>
<tr>
<td>20# Bond</td>
<td>103</td>
<td>258</td>
<td>155</td>
</tr>
<tr>
<td>110# Bond</td>
<td>106</td>
<td>217</td>
<td>111</td>
</tr>
<tr>
<td>Wrinkled 20# Bond</td>
<td>98</td>
<td>195</td>
<td>97</td>
</tr>
<tr>
<td>Cardboard</td>
<td>75</td>
<td>195</td>
<td>120</td>
</tr>
<tr>
<td>Manila Folder</td>
<td>97</td>
<td>270</td>
<td>173</td>
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<td>Photograph</td>
<td>115</td>
<td>Note 1</td>
<td>Note 1</td>
</tr>
<tr>
<td>Pink Receipt</td>
<td>78</td>
<td>144</td>
<td>66</td>
</tr>
<tr>
<td>Onion Sheet</td>
<td>99</td>
<td>225</td>
<td>126</td>
</tr>
<tr>
<td>Bank Check</td>
<td>90</td>
<td>266</td>
<td>176</td>
</tr>
<tr>
<td>Newspaper</td>
<td>90</td>
<td>204</td>
<td>114</td>
</tr>
</tbody>
</table>

Table 4-2 Material Effects on Phase Shift, 0.44" Transmitter to Receiver

Note 1 – Test not conducted with 2 photographs.
<table>
<thead>
<tr>
<th>Material</th>
<th>Phase Delta w/ 1 document</th>
<th>Phase Delta w/ 2 documents</th>
<th>Delta from 1 to 2 documents</th>
</tr>
</thead>
<tbody>
<tr>
<td>20# Bond</td>
<td>6.9</td>
<td>1.4</td>
<td>5.5</td>
</tr>
<tr>
<td>110# Bond</td>
<td>23.4</td>
<td>-13.6</td>
<td>37</td>
</tr>
<tr>
<td>Wrinkled 20# Bond</td>
<td>-39.6</td>
<td>19.6</td>
<td>-20</td>
</tr>
<tr>
<td>Cardboard</td>
<td>-26.6</td>
<td>55.4</td>
<td>-82</td>
</tr>
<tr>
<td>Manila Folder</td>
<td>-15.6</td>
<td>-101.6</td>
<td>86</td>
</tr>
<tr>
<td>Photograph</td>
<td>-37.6</td>
<td>Note 1</td>
<td>Note 1</td>
</tr>
<tr>
<td>Pink Receipt</td>
<td>-38.4</td>
<td>-26.6</td>
<td>-11.8</td>
</tr>
<tr>
<td>Onion Sheet</td>
<td>9.4</td>
<td>34.4</td>
<td>-25</td>
</tr>
<tr>
<td>Bank Check</td>
<td>-48.2</td>
<td>80.4</td>
<td>-128.6</td>
</tr>
<tr>
<td>Newspaper</td>
<td>8.6</td>
<td>-57.6</td>
<td>66.2</td>
</tr>
</tbody>
</table>

Table 4-3 Distance Effects on Phase Shift from 0.132” to 0.44”

Note 1 – Test not conducted with 2 photographs.
<table>
<thead>
<tr>
<th>Material</th>
<th>Amplitude w/ 1 document</th>
<th>Amplitude w/ 2 documents</th>
<th>Amplitude w/ 3 documents</th>
<th>Delta from 1 to 2 documents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nothing</td>
<td>628-mv</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>20# Bond</td>
<td>29.5-mv</td>
<td>4.6-mv</td>
<td>1.24-mv</td>
<td>-24.9-mv</td>
</tr>
<tr>
<td>110# Bond</td>
<td>7.0-mv</td>
<td>9.4-mv</td>
<td>1.22-mv</td>
<td>+2.4-mv</td>
</tr>
<tr>
<td>Wrinkled 20# Bond</td>
<td>46.6-mv</td>
<td>12.2-mv</td>
<td>1.40-mv</td>
<td>-34.4-mv</td>
</tr>
<tr>
<td>Cardboard</td>
<td>4.2-mv</td>
<td>4.6-mv</td>
<td>Note 2</td>
<td>+0.4-mv</td>
</tr>
<tr>
<td>Manila Folder</td>
<td>9.8-mv</td>
<td>4.3-mv</td>
<td>Note 2</td>
<td>-5.5-mv</td>
</tr>
<tr>
<td>Photograph</td>
<td>9.6-mv</td>
<td>Note 1</td>
<td>Note 2</td>
<td>Note 1</td>
</tr>
<tr>
<td>Pink Receipt</td>
<td>43.0-mv</td>
<td>31.8-mv</td>
<td>3.92-mv</td>
<td>-11.2-mv</td>
</tr>
<tr>
<td>Onion Sheet</td>
<td>60.6-mv</td>
<td>29.0-mv</td>
<td>8.92-mv</td>
<td>-31.6-mv</td>
</tr>
<tr>
<td>Bank Check</td>
<td>23.5-mv</td>
<td>13.9-mv</td>
<td>0.2-mv</td>
<td>-9.6-mv</td>
</tr>
<tr>
<td>Newspaper</td>
<td>70.2-mv</td>
<td>51.8-mv</td>
<td>5.02-mv</td>
<td>-18.4-mv</td>
</tr>
</tbody>
</table>

Table 4-4 Material Effects on Amplitude, 0.44” Transmitter to Receiver

Note 1 – Test not conducted with 2 photographs.
Note 2 – Signal was too small to measure.

4.1.2 Effects of Distance between Transmitter and Receiver

Testing was done to determine the variation in the received signal as the distance between the ultrasonic transmitter and ultrasonic receiver was changed. This variability is important because there are mechanical tolerances in the actual production of a document scanner and changes due to expansion...
as the document scanner warms up. If there are any points where the output changes a large amount with a small change in distance, these areas should be avoided, as it would cause problems in actual use. The concern is that the operating point is on an area of the change curve that has a large slope. Here a small distance change would cause a large electrical change. The mechanical tolerance was determined to be a maximum of +/-0.5mm due to manufacturing variability and thermal expansion.[1]

Figure 13 shows the changes of the voltage output from the ultrasonic receiver with paper present over the range of approximately one inch. This Figure contains all the maximums and minimums over this one inch range. The swing in the output level is larger with a change in distance when there is a shorter distance between the ultrasonic transmitter and ultrasonic receiver. This swing becomes smaller as the separation becomes larger. Although this is more of a swing that would be ideal to have, it can be dealt with since it is known and a less sensitive area can be selected.
Figure 13 Receiver Output vs. Paper Distance, with Paper

Figure 14 shows the effects of changing the distance from the ultrasonic transmitter to receiver over approximately a one inch range on the output voltage without paper in the ultrasound path. The same approach was taken as in Figure 13 to obtain all the minimums and maximums. There is a similar effect on the output with distance that also decreases with an increase in distance. Both of these test results are combined in Figure 15 to aid in the selection process, although much detail is lost in Figure 15 due to the amplitude differences.
Figure 14 Receiver Output vs. Distance, without Paper

Figure 15 Receiver Output vs. Distance, with and without Paper
Figure 16 shows the changes of the voltage output from the ultrasonic receiver without paper present over the range of one inch, as in Figure 14. However, the ultrasonic transmitter was driven with a signal over the range of 1.0 volts (RMS) to 16.0 volts (RMS). This was done to determine if the relationship between the distance and the received level is dependent on the actual level that the ultrasonic transmitter is driven with. Clearly this relationship is independent of the voltage applied to the ultrasonic transmitter. This indicated that the drive voltage to the ultrasonic transmitter could be adjusted during calibration without effecting this relationship.
Figure 16 Receiver Output vs. Distance as Transmitter Voltage is Varied

Clearly from this testing the separation between the ultrasonic transmitter and ultrasonic receiver should be as close to the full inch as possible to decrease this output swing. It is also found from Figures 13 through 16 that the actual output falls off very slowly from approximately 0.3 inches to 1.0 inches and usable output levels are obtained over this range.
4.1.3 Effects of Frequency

The original design approach was going to require a phase adjustment during the calibration process to allow for the full dynamic range of the phase detector, as described in the calibration section above. During experimentation, it was determined that changing the frequency of the transmitted ultrasonic waves could perform a fine-phase adjustment. Since the piezoelectric ultrasonic transmitter is a resonant crystal, there is a limited frequency range it will work over. The piezoelectric ultrasonic receiver also has a limited range it will function over. To determine this range, the ultrasonic transmitter and ultrasonic receiver were tested as a pair as the input frequency was varied while holding the driving voltage constant. This had the effect of determining the roll off effect of this pair as a function of frequency.

The results of the above test are shown in Figure 6. This test was conducted with a separation of ½ inch and 1 inch between the ultrasonic transmitter and ultrasonic receiver to insure the relationship is independent of the distance. By observing Figure 6, it is clear that at least 40% of the peak signal received would be obtained over the range of 38 kHz to 42 kHz. This range was selected because it was found during experimentation that a 2 kHz change in frequency resulted in approximately a 180-degree phase shift, the amount needed for the fine phase adjustment process. The manufacture of the ultrasonic transmitter and ultrasonic receiver was contacted after this experiment and they verified
that their product is rated for 40 kHz +/- 2 kHz, although there is no indication of this in their data book. Ideally the overall received level would have been large, however, this is a large enough signal level to use with and the driving voltage is adjusted during the calibration phase to compensate for this decrease in the received level.

4.1.4 Effects of Paper Position within the Ultrasound Path

Testing was conducted to determine the effect paper position with respect to the ultrasonic transmitter has on the phase of the received signal. Figure 17 shows a representation of the document and the ultrasound path. The nominal case is shown in Figure 17a where the paper is entering the midpoint between the ultrasonic transmitter and ultrasonic receiver. Figure 17b shows a representation of the paper when it is fully in the ultrasound path in the nominal case. Some of the ultrasound is passed through the document and some is reflect when it reaches the surface of the paper. The reflected ultrasound waves includes that which reflects from both surface interfaces, that is, the air to paper interface and the paper to air interfaces. Figure 17c shows a representation of the paper when it is closer to the ultrasonic transmitter and Figure 17d shows a representation of the paper when it is closer to the ultrasonic receiver.
Figure 17 Relationship between Paper and Ultrasound Path
Testing was conducted to determine the effects of changing the position of the paper with the ultrasound path as it moved with respect to the ultrasonic transmitter, that is, as the paper moved from the position shown in Figure 17c to the position shown in Figure 17d. This test needed to be conducted as the distance between the ultrasonic transmitter and ultrasonic receiver was also varied. This resulted in a large amount of data that is shown in Figures 18 through 35. The data were all included for clarification of these results.

Ideally, there would be no change in the phase shift as the distance between the ultrasonic transmitter and ultrasonic receiver was varied or as the paper position within the ultrasound path varied. This would allow the distance between the ultrasonic transmitter and ultrasonic receiver to be selected for the largest received amplitude and it would also eliminate the variations during operation due to thermal expansion. However, the phase shift does change as the distance between the ultrasonic transmitter and ultrasonic receiver changes because the wavelength of the ultrasound is less than an inch. By changing this distance, the received signal has a different phase relationship with the transmitted signal. The paper also moves around within the ultrasound path as it passes through the document transport and this can not be eliminated completely. Both of these cause a phase shift that needs to be characterized and addressed.
Figure 18 combines the phase shift as the paper is moved from the ultrasonic transmitter toward the ultrasonic receiver and as the ultrasound path is varied in 0.1 inch steps between 1.0 inches and 0.7 inches. Examining these data combine in this method shows that the smallest phase changes for paper movement is obtain when the paper is near the center of the ultrasound path. Examination of Figures 18, 20, 22, 24, 26, 28, 30, 32 and 34 confirm this to be the case. Clearly the closer the paper is to the center of the ultrasound path and the less it moves within this path, the less the phase changes due to paper movement. This results in a decrease in the measured phase shift errors with the result that the determination of multiple document feeds is more accurate and has the ability to be more document-independent.

Figure 19 combines the amplitude as the paper is moved from the ultrasonic transmitter toward the ultrasonic receiver and as the ultrasound path is varied in 0.1 inch steps between 1.0 inches and 0.7 inches, as in Figure 18. Examining the data combines in this method does not show any clear indication of a flat zone over this range of distances for the amplitude. Examination of figures 21, 23, 25, 27, 29, 31, 33 and 35 confirm this although there is a flat area in figure 31.
Figure 18 Phase Shift vs. Paper Distance from Transmitter Composite

Figure 19 Amplitude vs. Paper Distance from Transmitter Composite
Figure 20 Phase Shift vs. Paper Distance from Transmitter (#1)

Figure 21 Amplitude vs. Paper Distance from Transmitter (#1)
Figure 22 Phase Shift vs. Paper Distance from Transmitter (#2)

Figure 23 Amplitude vs. Paper Distance from Transmitter (#2)
Figure 24 Phase Shift vs. Paper Distance from Transmitter (#3)

Figure 25 Amplitude vs. Paper Distance from Transmitter (#3)
Figure 26 Phase Shift vs. Paper Distance from Transmitter (#4)

Figure 27 Amplitude vs. Paper Distance from Transmitter (#4)
Figure 28 Phase Shift vs. Paper Distance from Transmitter (#5)

Figure 29 Amplitude vs. Paper Distance from Transmitter (#5)
Figure 30 Phase Shift vs. Paper Distance from Transmitter (#6)

Figure 31 Amplitude vs. Paper Distance from Transmitter (#6)
Figure 32 Phase Shift vs. Paper Distance from Transmitter (#7)

Figure 33 Amplitude vs. Paper Distance from Transmitter (#7)
Figure 34 Phase Shift vs. Paper Distance from Transmitter (#8)

Figure 35 Amplitude vs. Paper Distance from Transmitter (#8)
The data in Figures 36 through 44 is the same data as in Figures 18, 20, 22, 24, 26, 28, 30, 32 and 34 rearranged to show the phase shift with the paper a fixed distance from the ultrasonic transmitter as the distance between the ultrasonic transmitter and ultrasonic receiver is varied. This distance between the ultrasonic transmitter and ultrasonic receiver is varied from 1.0 to 0.2 inches in 0.1 inch steps. This data clearly indicates the smallest changes are near the center of the ultrasound path.

Figure 36 Phase Shift vs. Transmitter to Receiver Distance Composite
Figure 37 Phase Shift vs. Transmitter to Receiver Distance (#1)

Figure 38 Phase Shift vs. Transmitter to Receiver Distance (#2)
Figure 39 Phase Shift vs. Transmitter to Receiver Distance (#3)

Figure 40 Phase Shift vs. Transmitter to Receiver Distance (#4)
Figure 41 Phase Shift vs. Transmitter to Receiver Distance (#5)

Figure 42 Phase Shift vs. Transmitter to Receiver Distance (#6)
(0.6" Transmitter to Paper)

Figure 43 Phase Shift vs. Transmitter to Receiver Distance (#7)

(0.7" Transmitter to Paper)

Figure 44 Phase Shift vs. Transmitter to Receiver Distance (#8)
Figure 18 and Figures 20 through 36 show that in general, as the distance between the ultrasound path is reduced, there is more variation in the phase shift as the paper position changes. The best results are obtained with a distance of 0.9 inches for the ultrasound path. Figure 21 shows that there is approximately no phase change for the range of 0.3 inches to 0.6 inches of the center 1/3 of the ultrasound path. If the length was selected to be 0.9 inches for the distance between the ultrasonic transmitter and ultrasonic receiver, then the paper could move over the center 0.3 inches with no phase change and this provides us with the idea situation under this one condition. It is worth noting that the amplitude does change through this range, as in Figure 19. Ideally the amplitude would remain constant over this same distance change.

4.1.5 Effects of Paper Angle within the Ultrasound Path

All the bench testing involved a micrometer movement mechanical assembly that provides accurate and repeatable position adjustments for the distance between the ultrasonic transmitter and ultrasonic receiver. This mechanical assembly has no provision for paper rotation within the ultrasound path. The expense to build a mechanical assembly that would provide this functionality was cost prohibitive and a lower cost alternative method was used for this testing. The angle rotation testing was conducted with mechanical supports and the angles were set using a protractor and visual estimations. The paper was
centered within the ultrasound path after the angle of rotation was set to take the
data measurements. This approach allowed a lot of room for error and, therefore, the full test was repeated two times and the average was used to reduce this error. These errors could have been reduced even more if the testing was repeated many times and the average was taken, however, it was very time consuming to make adjustments for repeated measurements and the results were close for both sets of data taken and averaged for the listed results. Although there was potential for errors due to visual estimations in the data used for this test, it still was determined to be useful since it shows the general trend of the change in phase and amplitude as the paper was rotated. If this testing had shown an advantage to this approach, additional and more accurate testing would have been justified.

The testing was only conducted with a 1.0 inch ultrasound path since this allowed for the largest angle of rotation before the paper made contact with the ultrasonic transmitter and ultrasonic receiver. The maximum angle of rotation this test was conducted at was limited to 30-degrees before the paper made contact with the ultrasonic transmitter or the ultrasonic receiver.

Testing was conducted to determine the effect of paper angle with respect to the ultrasound path on the phase and amplitude of the received signal. Figure 17e shows a representation of the paper when it is fully in the ultrasound path with the paper at an angle to the straight line between the ultrasonic transmitter and
ultrasonic receiver. The nominal case is shown in Figure 17b with the paper perpendicular to centerline of the path the ultrasound takes. Panasonic uses this approach in their document scanners and, therefore, this investigation was warranted. However, Panasonic uses the “ultrasonic amplitude method” using ultrasound at 220 kHz. The data in Figure 46 shows there is a reduction in received signal amplitude as the angle is increased and this would result in a larger ratio of the received signal with paper as compared to no paper. Rotation offers some minor advantages to the amplitude only method.

Figure 45 shows the amplitude of the received signal as the paper is rotated. The idea situation would be where the phase shift and amplitude either did not change or only changed in one direction. Figure 46 shows the effect of rotating the paper within the ultrasound path on the received signal. For the first 5-degrees of rotation, there is basically no change in the phase shift as the ultrasound passes through one sheet of 20# bond. As this angle is increased beyond 5-degrees there is a phase shift and this phase shift increases and decreases through the angle of rotation.
Figure 45 Phase Shift Change vs. Rotation Angle

Figure 46 Amplitude vs. Rotation Angle of Paper
These graphs show that if the paper is kept relatively flat within the ultrasound path there will be no phase shift concerns for small angle changes. There will be amplitude changes but these changes are small enough that the decision algorithm within the microcontroller will not be mislead.
5 FUTURE WORK AND ALTERNATE APPLICATIONS

5.1 Alternate Approach – Time Delay Measurement

The "ultrasonic document detector circuit" uses a continuous sound wave from the ultrasonic transmitter. Amplitude and phase information is interpreted from the signal at the receiver to determine the number of documents present. A different approach that might offer some advantages is to use a single pulse one cycle long to the transmitter. Amplitude and time delay would be interpreted from the signal at the receiver.

This time delay approach would reduce the complexity of the electronics by requiring only a timer that is started when the pulse is sent from the transmitter and stopped when the pulse arrives at the receiver. This would perform the same functionality that the state machine and counter inside the EPDL does with the approach used. The time differential would provide data that is dependent on the number of documents in a similar way that the phase shift method works with each document the ultrasonic waves pass through adding delay. The amplitude detection could still be performed using the peak detector developed for the "ultrasonic document detector circuit" with just an increase in the time constant to compensate for the reduced number of peaks applied to this peak detector.
Experimentation was conducted to test the viability of this approach, however, it was determined that the Murata ultrasonic transmitters take approximately twenty cycles to reach full output and more than ten to reach an output level high enough to be usable. The Piezoelectric transmitters are resonant devices that require multiple drive cycles to reach full output. MuRata Manufacturing and Panasonic, two manufactures of ultrasonic devices used for testing, were contacted to determine the availability of ultrasonic transmitters that produced outputs faster. Neither had any products that would work and could offer no suggests on ways to speed their products up.

Among the approaches that could be taken for producing a single pulse is an electronic method making use of a dynamic transducer such as a “tweeter” or high frequency speaker and a mechanical method making use of a shutter or chopper. The shutter or chopper would be placed in front of a resonant ultrasonic transmitter such as is used in the “ultrasonic document detector circuit”. The shutter would work in much the same way as a camera shutter does by opening at a known time. This would apply the ultrasound at a known time and could easily be under electronic control. The chopper could be implemented with a rotating wheel with cuts or slits in it. The movement of this wheel could either be under electronic control so its position is known or it could be monitored with a sensor for determination of its position. Both of these methods would make use of a continuous output ultrasonic transmitter with a mechanical method to apply the ultrasonic signal at a known time.
A dynamic transducer is physically larger, higher cost and requires more drive power due to the reduction in efficiency since it is not a resonant device. It does have the advantage of functioning over a wider frequency range and having a more constant output level over this wider frequency range. This flexibility in the drive frequency of a dynamic transducer would have an advantage in the phase calibration method that varied the drive frequency as described in Chapter 3.

The mechanical shutter or chopper is a very complicated and expensive solution, is lower reliability and is complex to implement. This method also needs a more involved calibration process to adjust for the mechanical tolerances, as it would be required to have a very accurate knowledge of the position of the slit or cut in the wheel.

5.2 Improvements on Present Approach

The time delay approach could be implemented in parallel with the phase shift and amplitude approaches in the same system to provide additional data to the decision algorithm within the microcontroller. This additional data would allow an algorithm that is more document-independent and more robust in its determination of multiple document feeds. In the approached implemented for the “ultrasonic document detector circuit”, there is a “gray area” where the phase shift and the amplitude methods indicate different results. For example, two
onion sheets might have an amplitude that is the same level as one 110# bond sheet but the phase shift is larger. This situation is handled by using the amplitude method for certain amplitude ranges and the phase shift method for other amplitude ranges. The time delay method could be used as a “tie breaker” if used in conjunction with the phase shift and amplitude methods or it could be used to select either the phase shift or amplitude method. Various approaches could be investigated to determine the proper selection of the method to use.

In some applications it is critical that no documents pass through a document scanner unscanned such as legal documents. In these applications the additional complexity of the combination of the three approaches just discussed might be justified. It would also be possible to incorporate a "paper contact method" such as the Hall Effect Sensor method to reduce the chances of a missed multiple document feed by performing a second test. The contact sensor could be used only during critical applications and then moved out of the way during less critical applications to reduce the chances of a paper jam due to the contact with the documents.
5.3 Areas for Improved Detection of Multiple Document Feeds

The need exists within a document transport to know the position of the documents to enable the Scan Engine to turn on the automatic document feeder and to ensure the documents have left the system. Traditional methods for detecting the document position includes optical detectors and, in lower cost systems, contact sensors. The disadvantages of the contact sensors were discussed previous. The optical sensors generally use infrared energy to reduce interference from ambient light. These optical sensors can not be used for multiple document detection due to the high attenuation of the infrared energy as it passes through the documents. In addition, the energy reduction varies between different document materials, which precludes document-independent multiple document detection with infrared sensors.

Since there is a need to both determine the position of the documents within the document transport and the presence of multiple document feeds, methods to perform both these functions must exist within a document scanner. The position sensors can not be used to detect multiple document feeds, however, the "ultrasonic document detector circuit" can be used to determine the position of the documents. By combining this functionality, the overall system complexity and cost is reduced by eliminating one of the optical sensors. Only one of the optical sensors can be replaced since there only needs to be one ultrasonic multiple document detector within a document scanner. This additional
functionality can be implemented within the microcontroller with no additional hardware cost or it can be implemented in hardware with a comparator monitoring the amplitude level to determine the presence of a document.

5.4 Applications Beyond Document Scanners

5.4.1 Applications within Copiers

This "ultrasonic document detector circuit" has additional applications in photocopiers. All photocopiers have paper feeders that pickup blank paper from a hopper and transport this paper to the apparatus that produces the image. This paper with the image is then deposited into an output bin. If multiple documents are fed into the copier, paper jams may result or blank papers may be inserted within the copies. With the application of the "ultrasonic document detector circuit" at the paper feeder input, the copier could be stopped before a multiple document feed or a paper jam took place. This feature would be especially useful by preventing the paper jam from occurring within the copier since paper jams can be difficult to clear inside the copier. However, since the paper within a copier is very uniform and clean, a document-independent solution such as "ultrasonic document detector circuit" might not be required. A simpler approach would provide adequate detection such as phase detection or amplitude detection alone.
Many photocopiers have an automatic document feeder that transports the documents to be copied from an input bin to the scan engine. Often these documents are of very poor condition with tears or staples, resulting in more than one document being drawn into the feeder. A multiple document detection system used in this application would have to be document-independent. This is an ideal application of the “ultrasonic document detector circuit” for the same reasons it works in a document scanner. This reapplication of this technology could be accomplished with almost no changes in the circuitry.

5.4.2 Detection of Paper Jams

During testing it was found that heavily wrinkled documents have a larger phase shift than paper of the same material that is not wrinkled. Testing of 20# bond indicated an additional 20 to 40-degrees of phase shift when the document is wrinkled. It is worth noting that this test was difficult to repeat for the same indicated phase shift since the amount of wrinkling was difficult to repeat. However, there was a clear indication of additional phase shift due to wrinkling. With additional testing a more precise relationship could be determined.

Using this additional phase shift the detection of a document that is wrinkling due to a paper jam could be detected and the feeder could be stopped before the document was heavily damaged. Proper placement of the ultrasonic
transmitter and ultrasonic receiver near the point where the paper jams are most likely to take place would result in detection of the paper jam before the document was seriously damage so the document feeder could be turned off. A patent is being pursued for this based on this author’s work.

5.4.3 Detection of Paper in a Continuous Roll

The “ultrasonic document detector circuit” could be extended to detect the presence of and wrinkling of paper for applications that use rolls of paper, such as newspaper printing and photographic film manufacturing. This method could detect the end of the roll, a break or a jam in the paper. This would be especially useful with sensitized photographic paper as no method using light can be implemented or the film will be partially exposed by this light.

Since all the paper on the roll would be yield approximately the same phase shift, a window of operation could be set with phase shifts outside this window indicating a problem. If the phase shift were above the window, a paper jam would be indicated. If the phase shift were below the window, a break in the paper or an end of roll would be indicated.
5.4.4 Ideas for Determining Presence of Inserts or Materials

Envelopes with inserts in them can be tested to determine the presence of those inserts by passing ultrasound through these envelopes and ensuring the phase shift and amplitude indicates the proper number of documents present. This has the advantage over methods such as weighing these envelopes because the testing can be conducted while the envelopes are moving through the processing equipment. In a similar way, the presence of a product within a box can be tested such as a bottle of vitamins within the packing box.
References:


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Bibliography:


Skahill, Kevin. VHDL For Programmable Logic. Addison-Wesley. 1996.

NOTE: This Bibliography only includes sources not already listed in the References Section.
Appendix A – Definitions:

**A/D Converter:** Analog-to-digital converter.

**AHDL:** Altera Hardware Descriptive Language. A hardware design entry language that is used by Altera’s MaxPlus compiler. It will only compile on Altera’s MaxPlus compiler.

**CCD:** Charge Coupled Device – used to capture the optical image of the document as it passes the document scanner or scan engine.

**COP Watchdog:** Circuit Operating Properly Watchdog – a self-monitoring circuit to protect against software failures which generates a system rest in case in the event the software is caught in a loop.

**CPU:** Central Processing Unit.

**Decision Algorithm:** The algorithm within the microcontroller that makes the determination of the presence of multiple document feeds.

**Document Feeder:** A mechanical device that takes documents from a holding tray and pulls them into a document transport.

**Document-independent:** Same results are obtained regardless of the document material.

**Document Scanner:** A device that scans documents and converts the image of that document into an electronic image.

**Document Transport:** A mechanical device that moves documents through a copier or scanner.

**EEPROM:** Electrically Erasable Programmable ROM – memory that is non-volatile and that can be rewritten. Typically this holds variables that will change and that need to be saved after the power is removed.

**EPLD:** Erasable Programmable Logic Device – an IC that has internal logic blocks that are combined to perform logic functions such as state machines and basic combinatorial functions. The input files for programming these devices can be VHDL, schematics or a combination of these.

**EPROM:** Electrically Programmable ROM – memory which is non volatile and can only be written or programmed once. Typically this would hold the source code and constants.
**Fishscope:** An electronic device used to locate fish underwater by transmitting ultrasound into the area of interest and observing the ultrasound reflections.

**Flywheel:** The ability of a Phase Lock Loop to continue to maintain lock with a temporary loss of input signal.

**Host Computer:** The computer that interfaces to the “ultrasonic document detector circuit”. The host computer controls the user interface, receives interrupts when a multiple document feed is detected and enables the required functionality on the “ultrasonic document detector circuit”.

**Interdocument Gap:** The space between documents as they are moving through the document transport. This space is effectively a time when there is no document present and it can be used as a reference for the calibration process performed by the “ultrasonic document detector circuit”.

**Linear Voltage Differential Transducer (LVDT):** A device used to measure short distances accurately by moving an arm composed of a magnetic material between two coils. A signal is applied to one coil and the level received by the second coil is used to indicate the distance. As this arm is moved out of the area between these two coils the magnetic coupling decreases and the received signal level decreases.

**Multiple document feed:** A situation where more than one document is fed into the document transport by the document feeder on a document scanner or copier.

**Nonhygroscopic:** Does not absorb moisture.

**OTP:** One Time Programmable – programmable memory that can not be erased or reprogrammed.

**PAL:** Programmable Array Logic – an IC that has programmable logic arranged in arrays that allows the designer to specify the nature of the product terms.

**Phase Shift Algorithm:** The algorithm within the EPLD that determines the phase shift between the transmitted and received ultrasonic signals.

**RAM:** Random-Access Memory – memory that is volatile. Typically used for variables by the software.

**ROM:** Read-Only Memory – memory that is non volatile and must be programmed. Typically used for the source code.
Self-documenting Code: Code written with variable name selection that indicates the function of the variables and code resulting in the need for little additional documentation.

Scan Engine: Hardware that captures the image of a document that is being scanned. This hardware includes the CCD, the electronic drive for the CCD and some image processing.

SCI: Serial Communications Interface. The SCI is asynchronous in the MC68HC711E9.

SPI: Serial Peripheral Interface. The SPI is synchronous in the MC68HC711E9.

Throughput: The number of documents that can be scanned in a given length of time.

"Ultrasonic Document Detector Circuit": The circuit developed for this paper.

Ultrasonic Receiver: A device which receives ultrasonic sound waves and converts them into an electrical signal proportional to the amplitude of that received sound wave. Those used in the "ultrasonic document detector circuit" are piezoelectric.

Ultrasonic: The ultrasonic waves that are produced by the ultrasonic transmitter and sensed by the ultrasonic receiver.

Ultrasonic Path: The path between the ultrasonic transmitter and ultrasonic receiver through which the ultrasonic waves pass. It is in this path that the documents pass when testing for the presence of multiple document feeds by the Ultrasonic Document Detector" Circuit.

Ultrasonic Transmitter: A device that transmits ultrasonic sound waves that are proportional to the amplitude of an applied electrical signal. Those used in the "ultrasonic document detector circuit" are piezoelectric.

User Interface: The interface between the host computer and the user operating the scanner. This contains a keyboard for the user to input data and a display for the user to receiver data.

VHDL: Very high speed integrated circuit Hardware Descriptive Language – a programming language used as a circuit description for the programming of programmable logic devices such as EPLDs.
/*========================================================*/

#include <wslxa.h>
#include "io.h"
#include "kodak.h"
#include "general.h"

extern void analog_digital();
extern void config();
extern void init_system();

extern void DelayMS();
extern char calibrate();
extern void print_char();
extern void print_int();
extern void eep_prog();
extern void cal_no_paper();

void power_on_test();
unsigned char amp_dbl_dtct();
unsigned char phase_dbl_dtct();
unsigned char tst_for_doc();
/* variables for this file only */
unsigned char amplitude_in_low;
unsigned char amplitude_in_medium;
unsigned char amplitude_in_high;

/* global variables */
unsigned char *eepage;
unsigned char *eepad;
unsigned char *eeload;
unsigned char *eecoct;
unsigned char *eegain;
unsigned char *shadow_PORTB;
unsigned char ref_phase;

void main()
{
    DelayMS(1000); /* Allow external circuitry to stabilize */
    init_system(); /* Setup system for operation */
    power_on_test(); /* Test on powerup */
    cal_no_paper(); /* Calibrate without paper present */

    /* Initialize variables */
    cli(); /* enable all interrupts */
    for(;;)
    {
        if ((amp dbl dtct() == TRUE) || (phase dbl dtct() == TRUE))
            setbit(PORTB, DOUBLE_DETECT);
        else
            clrbit(PORTB, DOUBLE_DETECT);

        if (tst_for_doc() == TRUE)
            setbit(PORTB, DOC_PRESENT);
        else
            clrbit(PORTB, DOC_PRESENT);
    } /* End of forever loop */

    return;
} /* end main*/

*******************************************************************************
* FUNCTION NAME: power_on_test()                                           *
* DESCRIPTION:                                                             *
*   This is power on test that flashes LEDs.                               *
*******************************************************************************
void power_on_test()
{
    setbit(PORTA, AMP_DB);
    DelayMS(300);
clrbit(PORTA, AMP_DBL);
setbit(PORTA, PHASE_DBL);
DelayMS(300);

crbit(PORTA, PHASE_DBL);
setbit(PORTB, DOC_PRESENT);
DelayMS(300);

crbit(PORTB, DOC_PRESENT);
setbit(PORTB, DOUBLE_DETECT);
DelayMS(300);

setbit(PORTB, DOUBLE_DETECT);
setbit(PORTB, CPU_OK);
}

/***************************************************************
* FUNCTION NAME: RTI_Int_Service()                             *
* DESCRIPTION:                                                *
*   This is RTI interrupt service routine. It sets transport moving or not flag and *
*   speed of the transport.                                   *
***************************************************************
Interrupt RTI_Int_Service()
{
  TFLG2 = RTIF;    /* clear the RTI interrupt flag */
}

/***************************************************************
* FUNCTION NAME: cop()                                         *
* DESCRIPTION:                                                *
***************************************************************
void cop()
{
}

/***************************************************************
* FUNCTION NAME: amp_dbl_dtct()                                *
* DESCRIPTION:                                                *
*   This is function to determine if an amp multiple document condition is detected. *
***************************************************************
unsigned char amp_dbl_dtct()
{
  unsigned char amp_dbl_prsnt;
  static unsigned char amp_dbl_count = 0;
if(read_A_D_peak() < VOLTAGE_ONE_PAGE) {
    setbit(PORTB, DOC_PRESENT); /* Signal there is a document */
    if(read_A_D_peak_ll() < VOLTAGE_MULTI_PAGE) { /* Tst if Multi*/
        if(amp_dbl_count < AMP_MAX_COUNT)
            amp_dbl_count += amp_dbl_count;
    } else {
        if(amp_dbl_count > AMP_MIN_COUNT)
            amp_dbl_count -= amp_dbl_count;
    }
}
else {

    clrbit(PORTB, DOC_PRESENT); /* Signal there is not doc*/
    adjust_no_paper();
}

if(amp_dbl_count >= AMP_MAX_COUNT) {
    setbit(PORTA, AMP_DBL); /* Signal there is a amp multi */
    amp_dbl_prsnt = TRUE;
} else {
    clrbit(PORTA, AMP_DBL); /* Signal there is not amp multi */
    amp_dbl_prsnt = FALSE;
}
return(amp_dbl_prsnt);
}

/*********************************************
* FUNCTION NAME: phase_dbl_dtct()
* DESCRIPTION:
* This is fctn to determine if an phase
* multiple doc condition is detected.
***********************************************/
unsigned char phase_dbl_dtct() {
    unsigned char phase_dbl_prsnt;
    unsigned char phase_shift;

    static unsigned char phase_dbl_count = 0;

    if(read_A_D_peak() < VOLTAGE_ONE_PAGE) {
        setbit(PORTB, DOC_PRESENT); /* Signal there is a document */
        if((PORTC - ref_phase) < 0)
            phase_shift = ((PORTC + 255) - ref_phase);
        else
            phase_shift = (PORTC - ref_phase);

        if(phase_shift > PHASE_MULTI_PAGE) { /* Test for Multipages */
            if(phase_dbl_count < PHASE_MAX_COUNT)
                phase_dbl_count += phase_dbl_count;
        }

        /* Signal there is a document */
        if(read_A_D_peak_ll() < VOLTAGE_MULTI_PAGE) { /* Tst if Multi*/
            if(amp_dbl_count < AMP_MAX_COUNT)
                amp_dbl_count += amp_dbl_count;
        } else {
            if(amp_dbl_count > AMP_MIN_COUNT)
                amp_dbl_count -= amp_dbl_count;
        }
    }
    else {

        clrbit(PORTB, DOC_PRESENT); /* Signal there is not doc*/
        adjust_no_paper();
    }

    if(amp_dbl_count >= AMP_MAX_COUNT) {
        setbit(PORTA, AMP_DBL); /* Signal there is a amp multi */
        amp_dbl_prsnt = TRUE;
    } else {
        clrbit(PORTA, AMP_DBL); /* Signal there is not amp multi */
        amp_dbl_prsnt = FALSE;
    }

    return(amp_dbl_prsnt);
}
else {
    if (phase_dbl_count > PHASE_MIN_COUNT)
        phase_dbl_count -= phase_dbl_count;
}
else {
    clrbit(PORTB, DOC_PRESENT); /* Signal there is not a document */
    adjust_no_paper();
}
if (phase_dbl_count >= PHASE_MAX_COUNT) {
    setbit(PORTA, PHASE_DBL); /* Signal there is a amp multi */
    phase_dbl_prsnt = TRUE;
} else {
    clrbit(PORTA, PHASE_DBL); /* Signal there is not an amp multi */
    phase_dbl_prsnt = FALSE;
}
return(phase_dbl_prsnt);

*******************************************************************************
*                      FUNCTION NAME: tst_for_doc()                           *
* DESCRIPTION:          This is fctn to determine if an document             *
* is detected.            *****************************************************************

unsigned char tst_for_doc()
{
    unsigned char doc_present;
    if (read_A_D_peak() <= PAPER_PRESENT)
        doc_present = TRUE;
    else
        doc_present = FALSE;

    return(doc_present);
}
/*************************************************************
* Module Name: %W% %G%
* Designer/Implementer's Name: Daniel P. Phinney
* Description: Used for caling the double detect board
  before beginning operation.
* Reference Drawings:
* Inputs: None
* Processing: None
* Outputs: None
* Modification History:
* -------------------------------
* Date      Name              Release Descpt of change
* (dd/mm/yy) Version
* -------------------------------
* 3/15/99   Daniel P. Phinney 1.0 Original
**************************************************************/
#include "kodak.h"
#include "io.h"
#include "general.h"
#include <string.h>

extern void DelayMS();
extern void Delay_hundred_US();
extern void eep_prog();
extern char read_sensor_manual();

/* global variables */
extern unsigned char *eebase;
extern unsigned char *eeupad;
extern unsigned char *eeload;
extern unsigned char *eedoct;
extern unsigned char *eegain;
extern unsigned char shadow_PORTB;

/* global to this file only */
unsigned char Z_value;

void setup_DAC();
/**********************************************************
* FUNCTION NAME: calibrate()
* DESCRIPTION:  This function determines doc thickness of 
*               documents used in the double detect systm.
*               
* PARAMETERS:      NAME I/O DESCRIPTION
*                 ---- -- --------
*                 none. 
* RETURN CODES:   None. 
***********************************************************/

char calibrate(unsigned char * doc_thickness, unsigned char * led_mode, 
unsigned char gain) 
{
  unsigned char temp_doc_thickness = ZERO;
  char under_detect = FALSE;

temp_doc_thickness = ZERO;

return(under_detect);
}

/*
**********************************************************
* FUNCTION NAME: cal_no_paper()
* DESCRIPTION:  This function sets up emitter with no docs 
*               in transport. The input from the detector is 
*               adjusted for full range use of DAC. This 
*               function is used after powerup.
*               
* PARAMETERS:      NAME I/O DESCRIPTION
*                 ---- -- --------
*                 none. 
* RETURN CODES:
***********************************************************/

void cal_no_paper() 
{
  unsigned char saved_upper_PORTB;
  unsigned char xmit_val;
  unsigned char a_d_pk;
  unsigned char adjust_passed;

  saved_upper_PORTB = shadow_PORTB & MASK_LOWER_B;
  xmit_val = XMIT_START_VAL;
  PORTB = xmit_val;
  a_d_pk = read_A_D_peak();

  while((a_d_pk > PAPER_PRESENT)&&(xmit_val != 0x1F) 
        &&(xmit_val != 0x00) 
        && !(RCVR_UP_LMT_LOW < a_d_pk < RCVR_UP_LMT_HGH)))

{
    if(a_d_pk < RCVR_UP_LMT_LOW) {
        xmit_val++;
    }
    else if(a_d_pk > RCVR_UP_LMT_HGH) {
        xmit_val--;
    }
    PORTB = xmit_val;
    DelayMS(1);
    a_d_pk = read_A_D_peak();
}

if((xmit_val != 0x1F) || (xmit_val != 0x00))
    setbit(PORTB, CPU_OK);
else
    clrbit(PORTB, CPU_OK);
PORTB = (xmit_val & saved_upper_PORTB);
return;
}

/*****************************************************/
/*
 * FUNCTION NAME: adjust_no_paper()
 * DESCRIPTION: This function makes minor adjustments
 * during interdocument gap.
 *
 * PARAMETERS: NAME I/O DESCPT
 * ---- --- --------
 * none.
 * RETURN CODES: none.
 *****************************************************/
void adjust_no_paper()
{
    extern unsigned char ref_phase;
    unsigned char saved_upper_PORTB;
    unsigned char xmit_val;
    unsigned char a_d_pk;
    unsigned char temp_phase_ref;

    saved_upper_PORTB = shadow_PORTB & MASK_LOWER_B;
    xmit_val = XMIT_START_VAL;
    PORTB = xmit_val;
    a_d_pk = read_A_D_peak();

    if((a_d_pk > PAPER_PRESENT) && (xmit_val != 0x1F) &&
        (xmit_val != 0x00) &&
        !(RCVR_UP_LMT_LOW < a_d_pk < RCVR_UP_LMT_HGH))
    {
        if(a_d_pk < RCVR_UP_LMT_LOW) {
            xmit_val++;
        }
    }
else if (a_d_pk > RCVR_UP_LMT_HGH) {
    xmit_val--;  
}

temp_phase_ref = PORTB;
if (a_d_pk > PAPER_PRESENT)
    ref_phase = temp_phase_ref;

if((xmit_val != 0x1F) || (xmit_val != 0x00))
    setbit(PORTB, CPU_OK);
else
    clrbit(PORTB, CPU_OK);
PORTB = (xmit_val & saved_upper_PORTB);

return;
}
#include "general.h"
#include "kodak.h"
#include "io.h"

FUNCTION NAME: read_A_D_peak()
DESCRIPTION: This routine reads the peak value from the analog section at peak_value.

unsigned char read_A_D_peak()
{
    unsigned char chl;

    chl = ADR1; /* read channel 1 of A/D */
    return(chl);
}

FUNCTION NAME: read_A_D_peak_11()
DESCRIPTION: This routine reads the peak value from the analog section at peak_value11.
unsigned char read_A_D_peak_11()
{
    unsigned char ch2;

    ch2 = ADR2; /* read channel 2 of A/D */

    return(ch2);
}

/***********************************************************
* FUNCTION NAME: read_A_D_peak_121()
* DESCRIPTION: This routine reads the peak value from the
* analog section at peak_valuel21.
****************************************************************/
unsigned char read_A_D_peak_121()
{
    unsigned char ch3;

    ch3 = ADR3; /* read channel 3 of A/D */

    return(ch3);
}
#include "io.h"
#include "kodak.h"
#include "general.h"

extern void read_sensor_init();

void RTI_Initialize();
void Pulse_Acc_Initialize();
void A_D_converter_Init();
void Clear_all_interrupt_flags();
void LED_Initialize();

void init_system(void)
{
    Clear_all_interrupt_flags();
    RTI_Initialize();
    Pulse_Acc_Initialize();
    A_D_converter_Init();
    LED_Initialize();
    read_sensor_init();

    return;
}
/**
 * FUNCTION NAME: RTI_Initialize()
 * DESCRIPTION: This function initializes RTI to interrupt every 32 ms.
 * PARAMETERS: NAME I/O DESCRIPTION
 * none. none.
 * RETURN CODES: none.
 */

void RTI_Initialize()
{
  /*
   * Set the time before we get an interrupt to 16.38 ms.
   * If RTR1 & RTR0 = 0 then RTI rate = 16.38 mS.
   */
  clrbit(PACTL, RTR0);
  setbit(PACTL, RTR1);
  /*
   * enable the interrupt and
   * clear the flag
   */
  setbit(TMSK2, RTII);
  TFLG2 = RTIF;

  return;
}

/**
 * FUNCTION NAME: Pulse_Acc_Initialize()
 * DESCRIPTION: This function initializes the Pulse Acc.
 * PARAMETERS: NAME I/O DESCRIPTION
 * none. none.
 * RETURN CODES: none.
 */

void Pulse_Acc_Initialize()
{
  /*
   * Enable the Pulse Acc. and set it for rise edge counts.
   */
  setbit(PACTL, PEDGE);
  setbit(PACTL, PAEN);
  /*
   * clear the flag
   * for polled mode
   */
  TFLG2 = PAOVI;

/* set accumulator count reg to 256 - 10 = 246 to determine * if transport is moving. */

PACNT = PULSE_ACC_BASE;

return;

/**********************************************************
* FUNCTION NAME: A/D_converter_Init() *
* DESCRIPTION: This function initializes A/D converter. *
* PARAMETERS: NAME I/O DESCRIPTION *
* none. *
* RETURN CODES: *
* none. *****************************************************/
void A_D_converter_Init()
{
/* Set A/D to continuous scan of multiple lower four channels. */
setbit(ADCTL, SCAN);
setbit(ADCTL, MULT);
clrbit(ADCTL, CD);
clrbit(ADCTL, CC);

return;

/***********************************************************
* FUNCTION NAME: Clear_all_interrupt_flags() *
* DESCRIPTION: This function initializes interrupt pending flags. *
* PARAMETERS: NAME I/O DESCRIPTION *
* none. *
* RETURN CODES: *
* none. ***************************************************/
void Clear_all_interrupt_flags()
{
/* clear all interrupt pending flags for port A */
TFLG1 = TFLG1_INIT;

/* clear IRQ pending flgs for Timer Overflow, RTI, Pulse Acc. */
TFLG2 = TFLG2_INIT;

return;
}
FUNCTION NAME: LED_Initialize()
DESCRIPTION: This function initializes outputs for PORT A.
PARAMETERS: Name I/O DESCRIPTION
* none.
RETURN CODES: none.

void LED_Initialize()
{
/****** setup outputs for port A *****************/
setbit(PACTL, DDRA3);

/****** clear or set outputs for port A and B *************/
PORTA = SETUP_PORTA;
PORTB = SETUP_PORTB;
return;
}
LIBRARY IEEE;
USE IEEE.std_logic_1164.all;
USE IEEE.std_logic_unsigned.all;

ENTITY uddds_pld IS PORT(
  amp_double : IN std_logic;
  double_dectect : IN std_logic;
  document_present : IN std_logic;
  epld_control1 : IN std_logic;
  epld_control2 : IN std_logic;
  phase_double : IN std_logic;
  reset, clock : IN std_logic;
  ref_signal : IN std_logic;
  sample_signal : IN std_logic;
  speed_pulses : IN std_logic;
  sw1 : IN std_logic;
  sw2 : IN std_logic;
  to_epld1 : IN std_logic;
  to_epld2 : IN std_logic;
  oe : IN std_logic;
  phase_value : OUT std_logic_vector (7 DOWNTO 0);
  epld_led : OUT std_logic;
  pulses_div8 : INOUT std_logic;
  pulses_div16 : INOUT std_logic;
  ultrasonic_clk : OUT std_logic;
  micro_clk : OUT std_logic);
END uddds_pld;

ARCHITECTURE statemac OF uddds_pld IS
  TYPE state_type IS (S0, S1, S2, S3, S4);

  SIGNAL present_state, next_state : state_type;
  SIGNAL count_temp : std_logic_vector (7 DOWNTO 0);
  SIGNAL clk_count : std_logic_vector (8 DOWNTO 0);
  SIGNAL epld_led_node : std_logic;
  SIGNAL micro_clk_node : std_logic;
  SIGNAL phase_value_node : std_logic_vector (7 DOWNTO 0);
  SIGNAL pulses_div2_node : std_logic;
  SIGNAL pulses_div4_node : std_logic;
SIGNAL pulses_div8_node : std_logic;
SIGNAL pulses_div16_node : std_logic;
SIGNAL ultrasonic_clk_node : std_logic;

CONSTANT divide_val : integer := 200;

BEGIN
fsm: PROCESS(clock, ref_signal, sample_signal, reset)
BEGIN
--Wait for low going edge on Reference Signal.
CASE present_state IS
  WHEN S0 =>
    IF (ref_signal = '0') THEN
      next_state <= S1;
    ELSE
      next_state <= present_state;
    END IF;

--Wait for high going edge on Reference Signal.
  WHEN S1 =>
    IF (ref_signal = '1' AND sample_signal = '0') THEN
      next_state <= S2;
    ELSIF (ref_signal = '1' AND sample_signal = '1') THEN
      next_state <= S3;
    ELSE
      next_state <= present_state;
    END IF;

--Count until Sample Signal is High.
  WHEN S2 =>
    IF (sample_signal = '1') THEN
      next_state <= S0;
    ELSE
      next_state <= present_state;
    END IF;

--Wait for high going edge on Sample Signal.
  WHEN S3 =>
    IF (sample_signal = '0') THEN
      next_state <= S4;
    ELSE
      next_state <= present_state;
    END IF;

--Wait for high going edge on Sample Signal.
  WHEN S4 =>
    IF (sample_signal = '1') THEN
      next_state <= S0;
    ELSE
      next_state <= present_state;
    END IF;
END CASE;
END PROCESS fsm;
COUNT: PROCESS (clock, present_state)
BEGIN
  IF (clock'EVENT AND clock = '1') THEN
    IF (reset = '0') THEN
      count_temp <= "00000000";
    ELSIF (present_state = S0) THEN
      phase_value_node <= count_temp;
    ELSIF (present_state = S1) THEN
      count_temp <= "00000001";
    ELSE
      count_temp <= count_temp + 1;
    END IF;
  END IF;
END PROCESS COUNT;

-- The following process handles clocking the statemachine --
state_clocked: PROCESS (reset, clock)
BEGIN
  IF (clock'EVENT AND clock = '1') THEN
    IF (reset = '0') THEN
      present_state <= S0;
    ELSE
      present_state <= next_state;
    END IF;
  END IF;
END PROCESS state_clocked;

-- The following process is for the Ultrasonic Clock --
ultra_clk: PROCESS (reset, clock)
BEGIN
  IF reset = '0' THEN
    ultrasonic_clk_node <= '0'; -- Set to 1 for 180 phase shift.
    clk_count <= "000000000";
  ELSIF (clock'EVENT AND clock = '1') THEN
    IF (clk_count = divide_val) THEN
      ultrasonic_clk_node <= NOT ultrasonic_clk_node;
      clk_count <= "000000001";
    ELSE
      clk_count <= clk_count + 1;
    END IF;
  END IF;
END PROCESS ultra_clk;

-- The following process is for the Microcontroller Clock --
u_clk: PROCESS (clock)
BEGIN
  IF (clock'EVENT AND clock = '1') THEN
    micro_clk_node <= NOT micro_clk_node;
END IF;
END PROCESS u_clk;

--The following process is for the Div Speed Pulses ----

div_spd2:PROCESS(speed_pulses)
BEGIN
  IF reset = '0' THEN
    pulses_div2_node <= '1';
  ELSIF (speed_pulses'EVENT AND speed_pulses = '1') THEN
    pulses_div2_node <= NOT pulses_div2_node;
  END IF;
END PROCESS div_spd2;

div_spd4:PROCESS(pulses_div2_node)
BEGIN
  IF reset = '0' THEN
    pulses_div4_node <= '1';
  ELSIF (pulses_div2_node'EVENT AND pulses_div2_node = '1') THEN
    pulses_div4_node <= NOT pulses_div4_node;
  END IF;
END PROCESS div_spd4;

div_spd8:PROCESS(pulses_div4_node)
BEGIN
  IF reset = '0' THEN
    pulses_div8_node <= '1';
  ELSIF (pulses_div4_node'EVENT AND pulses_div4_node = '1') THEN
    pulses_div8_node <= NOT pulses_div8_node;
  END IF;
END PROCESS div_spd8;

div_spdl6:PROCESS(pulses_div8_node)
BEGIN
  IF reset = '0' THEN
    pulses_divl6_node <= '1';
  ELSIF (pulses_div8_node'EVENT AND pulses_div8_node = '1') THEN
    pulses_divl6_node <= NOT pulses_divl6_node;
  END IF;
END PROCESS div_spdl6;

--The following is for LED Control and holding inputs ----

epld_led_node <= sw1 AND sw2 AND double_dectect AND
document_present AND epld_controll AND
epld_control2 ANDto_epld1 AND to_epld2 AND
amp_double AND phase_double;

--The following is for Tristating the Outputs ----

epld_led <= 'Z' WHEN (oe = '0') ELSE epld_led_node;
micro_clk <= 'Z' WHEN (oe = '0') ELSE micro_clk_node;
phase_value <= "ZZZZZZZZ" WHEN (oe = '0') ELSE phase_value_node;
pulses_div8 <= 'Z' WHEN (oe = '0') ELSE pulses_div8_node;
pulses_div16 <= 'Z' WHEN (oe = '0') ELSE pulses_div16_node;
ultrasonic_clk <= 'Z' WHEN (oe = '0') ELSE ultrasonic_clk_node;
END statemac;
Ultrasonic Received Signal Conditioning by Daniel Phinney

.WIDTH OUT = 80

.TRAN 5uS 5mS

.LIB /u/users2/phinney/spice/spice.models/national/op-amps/bjtoa.lib
.LIB /u/users2/phinney/spice/spice.models/diode/diode.lib
.LIB /u/users2/phinney/spice/spice.models/bipolar/bipolar.lib

* POWER SUPPLIES
V_PWR 100 0 DC 0V
V_N15VDC 200 0 DC -15V
V_P15VDC 300 0 DC 15V
V_SENSE 1 100 DC 0 AC 1 SIN(0 1 .4K)

R1 2 0 100K
R2 3 4 100K

C1 1 2 1u
C2 4 0 1u

*Pin Order for Op Amps is +IN -IN +POWER -POWER OUT
X_U1 2 4 300 200 3 LM324

.OP
.PRINT TRAN V(1) V(3) V(2)

.END
Ultrasonic Received Signal Conditioning by Daniel Phinney

.WIDTH OUT = 80

.TRAN 5uS 5mS

.LIB /u/users2/phinney/spice/spice.models/national/op-amps/bjtoa.lib
.LIB /u/users2/phinney/spice/spice.models/diode/diode.lib
.LIB /u/users2/phinney/spice/spice.models/bipolar/bipolar.lib

* POWER SUPPLIES
V_N15VDC 200 0 DC -12V
V_P15VDC 300 0 DC 12V
V_SENSE 1 0 DC 0 AC 1 SIN(0 1 .40K)

R1 1 2 10000000

C1 2 0 .1u

*Pin Order for Op Amps is +IN -IN +POWER -POWER OUT
X_U1 1 2 300 200 4 LM324

.OP

.PRINT TRAN V(1) V(2) V(4)

.END
Ultrasonic Received Signal Conditioning by Daniel Phinney

.WIDTH OUT = 80
.TRAN .05uS .05mS

.LIB /u/users2/phinney/spice/spice.models/national/op-amps/bjtoa.lib
.LIB /u/users2/phinney/spice/spice.models/diode/diode.lib
.LIB /u/users2/phinney/spice/spice.models/bipolar/bipolar.lib

* POWER SUPPLIES
V_PWR 100 0 DC 0V
V_N15VDC 200 0 DC -5V
V_P15VDC 300 0 DC 5V
V_SENSE 1 100 DC 0 AC 1 SIN(0 1 40K)

R1 4 2 100000
C1 2 0 .1u

*Pin Order for Op Amps is +IN -IN +POWER -POWER OUT
X_U1 1 2 300 200 4 LM324

.OP
.PRINT TRAN V(1) V(2) V(4)

.END
## Notes:

1. **Unless otherwise specified:**
   - All resistances are in ohms.
   - All capacitances are in microfarads.

2. **Complete Design Components:**
   - Assy. Part #: TBV022
   - PCB Part #: TBV023
   - SW1 Sheet Part #: N/A

3. **Mounting Holes Are plated and grounded.**

4. **Metal standoffs for mounting.**

5. **Remove paint from mounting holes or use lock washers.**

6. **CTF's for testing -- none.**

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<td>SH.7</td>
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CONNECT VDD ON CPLD TO FILTERED SIDED

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<tr>
<th>SIGNAL NAME</th>
<th>EXPECTED SPEED</th>
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<tr>
<td>SPEED_PULSES</td>
<td>687.4 TICKS/INCH</td>
</tr>
<tr>
<td>PULSES_DIV4</td>
<td>171.9 TICKS/INCH</td>
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<tr>
<td>PULSES_DIV16</td>
<td>43.2 TICKS/INCH</td>
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<tr>
<td>ULTRASONIC_CLK</td>
<td>1 KHZ</td>
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EASTMAN KODAK COMPANY
DOUBLE DOCUMENT DETECT SYSTEM
DOUBLE DOCUMENT DETECT SYSTEM

NOTES:

1. UNLESS OTHERWISE SPECIFIED:
   ALL RESISTANCES ARE IN OHMS
   ALL CAPACITANCES ARE IN MICROFARADS

2. COMPLETE DESIGN COMPONENTS:
   ASSY. PART #: 1H6960C
   PCB PART #: 1H6961A
   SWI SHEET PART #: 1H6963A

3. MOUNTING HOLES ARE PLATED AND GROUNDED

4. METAL STANDOFFS FOR MOUNTING

5. REMOVE PAINT FROM MOUNTING HOLES
   OR USE LOCK WASHERS

6. CTF'S FOR TESTING -- NONE.

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DOUBLE DOCUMENT DETECTOR MAGNETICS SENSOR BIASING CIRCUIT:

SENSOR SENSITIVITY=20mV PER MIL
DESIRED SCALE-RV/20MV=1.04V/MIL
REQUIRED GAIN=(2.4V/MIL/0.020V/MIL)=120.
Rg=1053 OHMS
IF Rg=1000 OHMS, A=21 or 0.420V/MIL.

GAIN=2

Rg=1053

UNUSED

RANGE 0 TO 1V IF EXTRA RESISTOR IS NOT LOADED
RANGE 0 TO 1.25V IF EXTRA RESISTOR IS LOADED

DIFFERENTIAL AMPLIFIER:

420 mV PER MIL

DC OFFSET NULL
SET PER 40.25 VDC
AT VOUT:

RANGE 0 TO 5V

1000V/MIL

RANSMFT LTD.