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I am submitting herewith a thesis written by James Wayne Walker II entitled "Design and Implementation of an Object Sensing and Counting System" I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the degree of Master of Science, with a major in Electrical Engineering.

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DESIGN AND IMPLEMENTATION OF AN OBJECT SENSING AND COUNTING SYSTEM

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

James Wayne Walker II

August 1995

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ABSTRACT

A system for the detection and counting of small objects is presented. This system was designed, implemented, and tested successfully. The system can detect objects as small as 1 mm. Accuracy is maintained at flow rates of 110 objects/s although normal flow rates are generally less than 20 objects/s. Tests revealed an overall accuaracy of 99.867%.

This system works in conjunction with a small object counting machine. The counting machine separates the objects so that they fall through a small tube in a somewhat single-file fashion. The machine is designed specifically for handling and counting pharmaceutical pills that range in size from 1 to 25 mm. The pills fall through a clear plastic square tube where they are detected and counted by this system.

The majority of the circuitry was implemented in a complex programmable logic device (CPLD) chip. The chip interfaces with infrared light-emitting diode (IRLED) sensor circuits that produce voltage pulses as objects fall through the small tube. The chip uses a pattern recognition algorithm that interprets these pulses and produces a counter output that is read by the counting machine's microcontroller chip where count totals are tallied. The pattern recognition chip can detect two objects should they fall through simultaneously. The chip also eliminates double counts caused by objects that might fall in such a manner that two pulses are generated by one object. This thesis discusses three schemes for the arrangement of IRLEDs for detection of falling objects: steady beam arrays of IRLEDs, pulsed arrays of IRLEDs, and a single IRLED-lens combination with a single chip pixel array sensor.

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CHAPTER 1

INTRODUCTION

The accurate counting of objects is a very important part of controlling costs for many businesses today. This is especially true in the packaging or dispensing phase of product production. If too few pieces are packed in the container, the result is angry customers. If too many pieces are packed in the container, then inventory is "given away," resulting in higher costs or loss of profit to the business. Thus, accurate counting methods are important. However, these counting methods add to the cost of the product if the production flow rate is slowed. Thus, sensor/counting systems must try to maximize accuracy while not impeding product flow. The types of systems used to detect/recognize and count objects vary greatly in complexity and cost.

The remainder of this chapter surveys several types of counting systems as well as the motivation for the design presented in this paper. Chapter 2 provides the background information on how the design began and the framework, or restraints, placed on the design at the beginning. Chapter 3 presents several results on discrete light-emitting diode (LED) and phototransistor (PT) pair sensors with associated logic for detecting and counting objects. Designs where the LEDs are turned on constantly as well as pulsed LED designs are presented. Problems with these configurations are also discussed. Chapter 4 discusses the use of a pixel strip optical detector chip, and the necessary control, filtering, and image recognition algorithms are presented. Chapter 5

concludes the thesis by presenting the results of testing and a summary of work performed as well as suggestions for future work.

1.1 General Methods for Object Detection and Counting

There are currently several types of sensor/detector devices and systems on the market today to count objects [1]. These systems are mainly used in industrial applications on production lines to count parts as they are ejected from machines or for counting as parts are packaged [2],[3],[4]. The type of system employed depends mainly on the cost of the product being counted and the flow rate.

A popular way to determine the number of pieces in a particular package or container is by weight [5]. Most products available at a grocery store are packaged and sold by weight. Programmable scales are used to weigh a known number of samples to obtain an average weight. The empty container is placed on the scale and the scale is initialized to zero. As the product or objects to be counted are placed in the container, the count is determined by the increasing weight. When the container has the specified quantity, it is sent down the production line, another empty container is retrieved, and the product flow continues. This method of counting is most useful for objects of reasonable weight or if the cost of the product is so low that only an approximate count is needed.

Optical sensors and image processing techniques are often the choice for producing more accurate counts of objects. Cameras, computers, and sophisticated image processing software are used in many systems for the recognition and counting of objects as they flow through a production line [6]. A camera is mounted in a manner to monitor

the product flow path. The camera is connected to a video processing and data acquisition (DAQ) circuit board. This board is usually connected to a computer. Software is used to retrieve the image from the camera, via the DAQ board. The image is stored as an array in the computer's memory. Various filter algorithms are used to extract or highlight features from the image array. Area, circumference, averages of various features, as well as simple counting, can be done once the image array is in the computer.

Another similar method is the use of a light beam or an array of light beams and light-detecting sensors to form a "light curtain" that is placed in the product flow path [2],[3],[4]. When an object passes through the light beams, its shadow is detected by the sensor circuit, which produces a pulse. This pulse is used to trigger counting circuits or to signal other production/processing control equipment that a part has been ejected from a press or stamping machine, for example.

1.2 Motivation for This Design

This project stemmed directly from Dr. Frank Speckhart's efforts to design a system to count pharmaceutical pills. This system has been targeted for use in small pharmacies. This implies that the system should be small enough in sizes to sit on a desk or table and be used to count pills of a variety of size with no changes in fixtures required. The system must also be low enough in cost that it would be widely desirable for small pharmacies. Figure 1-1 shows the front view of the pill counting system.

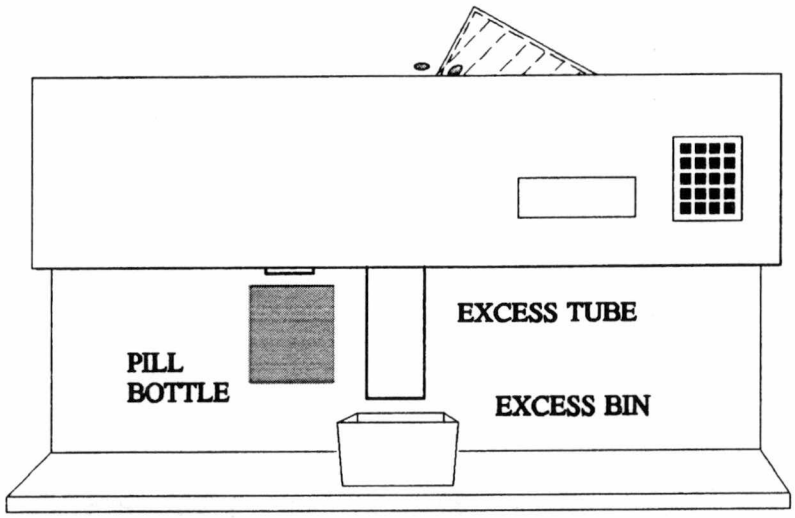


Figure 1-1 *Pill counting system.*

Assisting Dr. Speckhart was John Wilson [7], a student who programmed the microcontroller in the system. The system has been designed to separate and move pills in a single-file fashion. The pills pass through a sensor chute where they are counted and then collected in a standard pill container or bottle. The handling system is microcontroller based for control of the motors, keypad, display, sensing and counting. This system worked well with the exception of the sensing and counting functions. The system originally contained two beams formed by two LED-PT pairs. Pills, which come in a large variety of shapes and sizes, would tumble in such a manner that they would miss the beams, resulting in low-accuracy counts. The microcontroller circuit was nearly fully utilizied and could not support additional inputs from additional beam sensors. Dr. Speckhart began investigating a new sensor design and associated logic circuit. This first

circuit was pieced together with standard 74xx logic chips and one-shots. This circuit offered great improvements but required many individual chips. Hence, Dr. Speckhart contacted this author to replace the 74xx chips with one complex programmable logic device (CPLD). These devices offer a large number of reprogrammable resources in one compact package. This makes them well suited for development of designs.

1.3 System Requirements

The general goals of this design are to provide a system that counts objects of 1 to 25 mm in size at a flow rate of ~15 Hz with an accuracy greater than 99%. Although the pills generally flow in single-file fashion, the handling system should not be strictly limited to producing single-file object flow. The sensor portion should be able to handle objects varying in size from 1 to 25 mm without requiring any adapter chutes or funnels to be changed. The cost of the system itself should be kept as low possible to allow for competitive pricing. This thesis describes the design, implementation, and testing results of a system that meets all the above requirements.

CHAPTER 2

BACKGROUND INFORMATION

2.1 Counting Small Objects

In determining an adequate method of counting objects, consideration must be given to the size, shape, weight, transparency, and flow rate of the objects. Which parameters are important depends on the method of detection or sensing used. For example, counting pills by weight requires more expensive scales, because of the small weight of the pills. Also, the time taken to zero the scale and weigh samples impedes the flow rate. By the time the scale is programmed, one could simply count a small quantity by hand. For larger quantities the inaccuracies of the count would be costly for even the cheaper types of pills.

For optical methods, the size, shape, and transparency of the object are more important. For counting pills, image processing techniques are one of the more expensive methods because of the cost of the camera, computer, and software. Also, this method may not be suitable if the product flow rate is very high. Because of the data acquisition time and processing time, it may not be possible to count objects at real-time production flow rates [6]. Unfortunately, for this application, these techniques were immediately eliminated because of equipment costs.

Indeed, the method of choice for counting smaller objects seems to be the less costly LED-PT sensor. The configuration of these sensors depends on how the objects are handled. If all the objects are all the same size, the handling system is greatly simplified and so is the sensor. For example, consider a production and packaging system for any popular brand of aspirin. This type of system is dedicated to counting and packaging only one size object. The handling system can be optimized so that the aspirins fall single-file and can be accurately counted with only one or two sensors. However, a separate system or modifications must be performed to handle objects of a different size.

If the size of the object varies, then the handling system must be more general and less optimized to handle specific shapes. It must be large enough to accommodate the largest object to be counted, yet also be able to handle smaller objects. Also, handling odd-size parts at higher flow rates is more difficult because of the way these parts tumble and move through the handling system.

The sensor array for systems that handle multisized objects must also be more generic. This usually requires a light-curtain-type sensor array. This sensor must be wide enough so the largest objects pass through unimpeded, yet must have a resolution fine enough to detect the smaller objects. Odd-shape objects, objects that are transparent, or objects that have holes through the middle (like washers) pose even more difficulties.

Light-curtain-type sensors are commercially available [1]. However, a search of the professional literature and monthly trade publications turned up nothing on the design of these circuits. It is believed that the specific information on these systems is

proprietary and not available to the public. General information on how to use these products and product performance is available directly from the manufacturers of this equipment. Their product catalogs [2],[3],[4] show various types of sensors that can be mounted in the product flow path. These sensors generally are connected to other equipment for counting and controlling production equipment. Several companies were contacted and either provided literature and pricing information on light-curtain sensors or counter circuits, but not both. Also, no known commercially available sensor/counting system can detect objects that fell two at a time, but separated by some finite distance, for a cost that met the design requirements. Typical costs were over $1000 each for sensors. Thus, Dr. Speckhart concluded that currently available commercial sensors were too expensive and that a custom sensor system could be designed to meet the specific pill counting system's needs more economically.

2.2 Counting System

The Speckhart system counts a variety of small objects but is mainly aimed at the counting of pharmaceutical pills. To use the machine, the operator places a medicine bottle at the bottom of the sensor tube to collect the pills as they are processed through the machine. The operator then places a supply bottle of pills into the machine and uses the keypad to enter the number of pills to be counted. The operator next starts the machine by pressing one of three buttons, SP (small pill), MP (medium pill), or LP (large pill) depending on the estimated size of the pill being counted. Each of the three sizes selects a different speed at which to handle the pills, with SP being slowest and LP being

the fastest. Once the machine starts, the pills flow through the machine in near single-file fashion and are counted at the selected speed until the count is within two of the desired total. At this time the machine changes to a very slow speed and drops the pills through the sensor tube until the total has been reached. The machine then purges the excess pills into a tray where they are returned to the supply bottle. The total time it takes to count a number of pills varies with the number and size of the pill and how quickly the operator uses the keypad and loads/unloads the pill bottles. Generally, 100 aspirin can be counted in approximately 20 s. Figure 2-1 shows a detail of the pill handling system. The purge tube and excess tray are not shown.

The mechanical devices used to separate the pills consist of two main parts. The first is a rotating cup assembly into which pills are initially dumped. This cup contains wide and deeply cut threads on the inside. The cup rests on two rotating rubber wheels that rotate the cup, causing the pills to climb to the edge of the cup in an auger fashion. Because the threads are deep, the pills tend to tumble out of the cup in roughly single-file manner. The degree that this single-file alignment occurs depends of the size of the pills. The pills fall from the cup onto the second part, a rotating inverted cone. As the pills land on the cone, they roll or slide toward the bottom edge. The bottom edge of the cone is surrounded by a wall to guide the pills during rotation. The cone is driven by a stepper-motor, which is programmed to rotate the cone with a vibrating motion. This vibration during the cone's rotation further increases the single-file alignment of the pills. The pills travel along the wall at the bottom of the rotating cone until they reach an opening. At the opening in the wall of the rotating cone, the pills fall through a

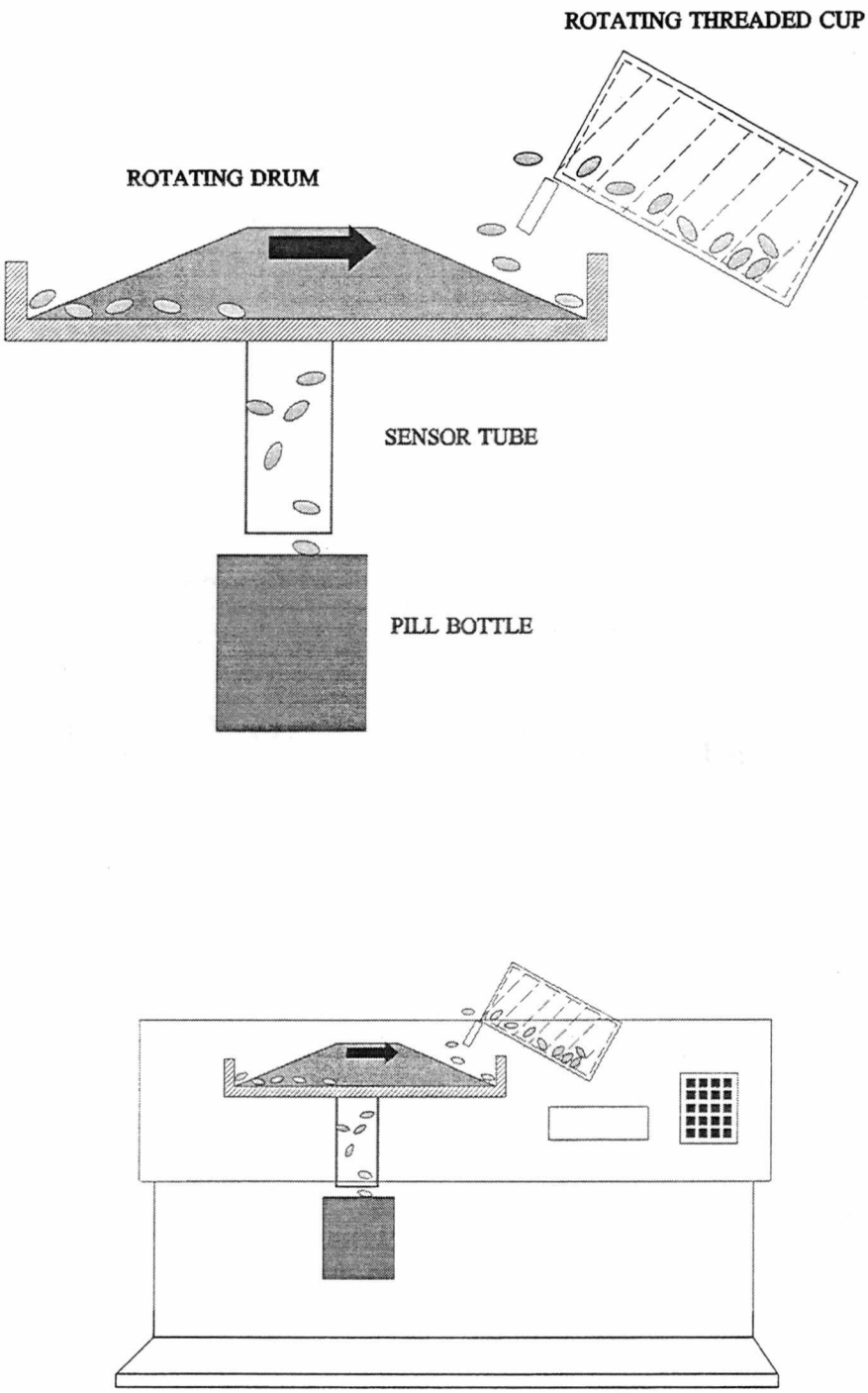


Figure 2-1 *Detail of the object handling system.*

rectangular sensor tube. This tube has the sensors for detecting the pills as they fall into the pill bottle at the other end. The tube shown in Figure 2-2(a) contains four LED-PT arrays. The circles shown on the side of the tube represent the holes for mounting the LEDs and PTs. To prevent any two beams mounted side-by-side from interfering with each other, the transmitters and receivers are alternated as shown in Figure 2-2b. The beams of one array cross the other array at a 90° angle. This forms a grid of infrared beams through which the pills fall. The strategy here is if two pills manage to fall through simultaneously and one pill is in the other's shadow from the front, the side sensors will still see two pills. Two levels of grids are used to increase the probability of detecting and counting the pill.

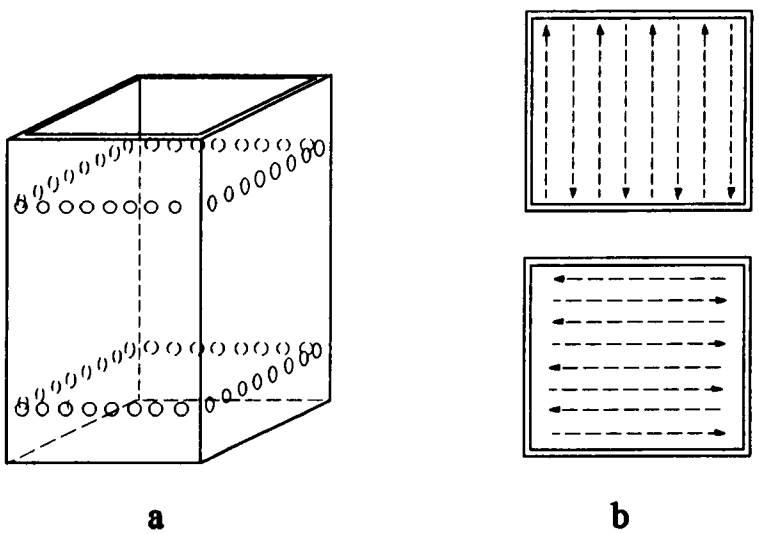


Figure 2-2 *(a) Sensor tube. (b) Beam orientations.*

The system block diagram is shown in Figure 2-3. The microcontroller continued to provide motor and display control as well as respond to operator commands entered via the keypad. However, instead of interfacing to the sensors directly, four separate sensor blocks handle these details and provide the microcontroller with a local count. The microcontroller is only required to poll the four local counts and make an overall decision of when to increment the total count that is displayed to the operator. The microcontroller polls the local counts often enough that it only needs a 2-bit binary counter as the local count for each sensor block. The following section describes Dr. Speckhart's original sensor block design with standard logic chips.

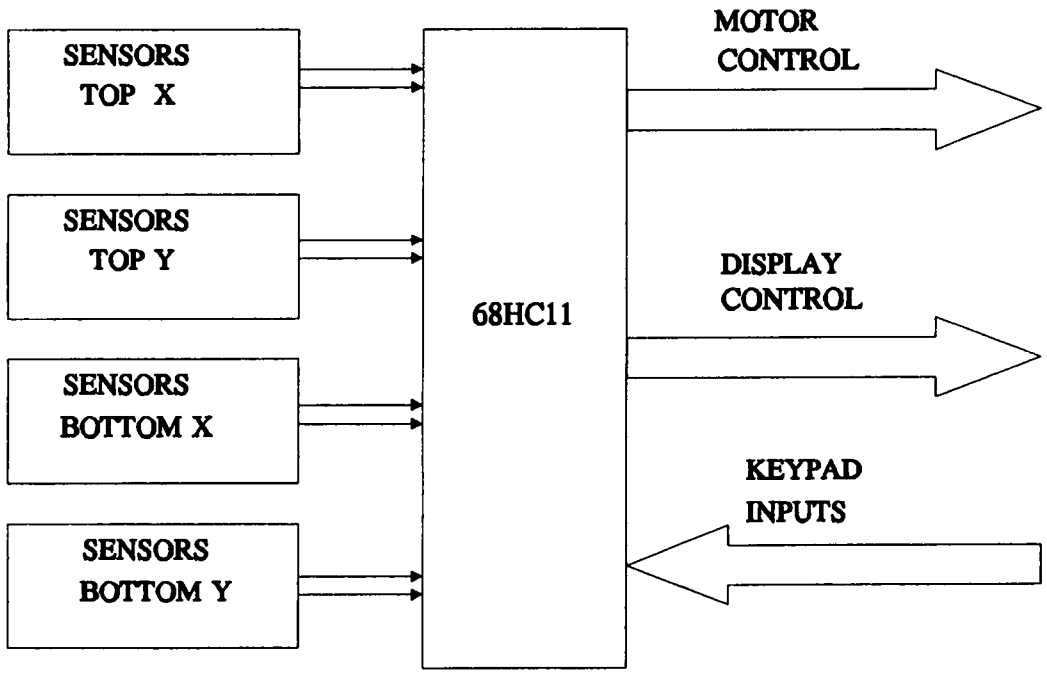


Figure 2-3 *Block diagram of system.*

2.3 Original Asynchronous Glue-Logic Circuit

Each sensor block required logic elements to convert the analog signals from the LED-PT pairs into a digital signal that can be used to increment the sensor block's local 2-bit counter. One of these circuits is shown in Figure 2-4. The outputs of each sensor array's PTs are connected to Schmitt triggers to give fast rising and falling edges and TTL level signals to the circuit and to provide hysteresis as the pill is falling into and out of the infrared beam. When no pill is present, the light from the LED in unobstructed and causes the PT to conduct. This provides an analog voltage of approximatly 3 V to the input of the Schmitt trigger. The output of the Schmitt trigger is a logic LOW. As a pill enters the sensor's beam, the pill's shadow causes the PT to turn off, resulting in an analog voltage of ~0 V to appear at the input of the Schmitt trigger, causing the output of the Schmitt trigger to go to a logical HIGH state.

For example, assume that a falling pill is first detected on channel 1, causing the output of channel 1's Schmitt trigger to go HIGH. This satisfies only one side of U1, which is shared by channels 1 and 2. At this point, assume that channel 2 has not yet detected the pill. Thus, U1's output is a LOW. This LOW cannot satisfy the inputs to channel 1's NOR-gate, U3, resulting in U3 producing a HIGH output. This HIGH output then enables U4. Shortly after that, channel 1's one-shot circuit, U2, goes HIGH, which passes through the enabled U4 for channel 1. If the pill later interrupts the beam on channel 2 the shared AND-gate, U1, is then satisfied. This drives the output of both U3 and U7 LOW, effectively disabling channels 1 and 2 from processing further pulses. Channel 2's logic also disables channel 3 from firing. If the pill falls into channel 3's

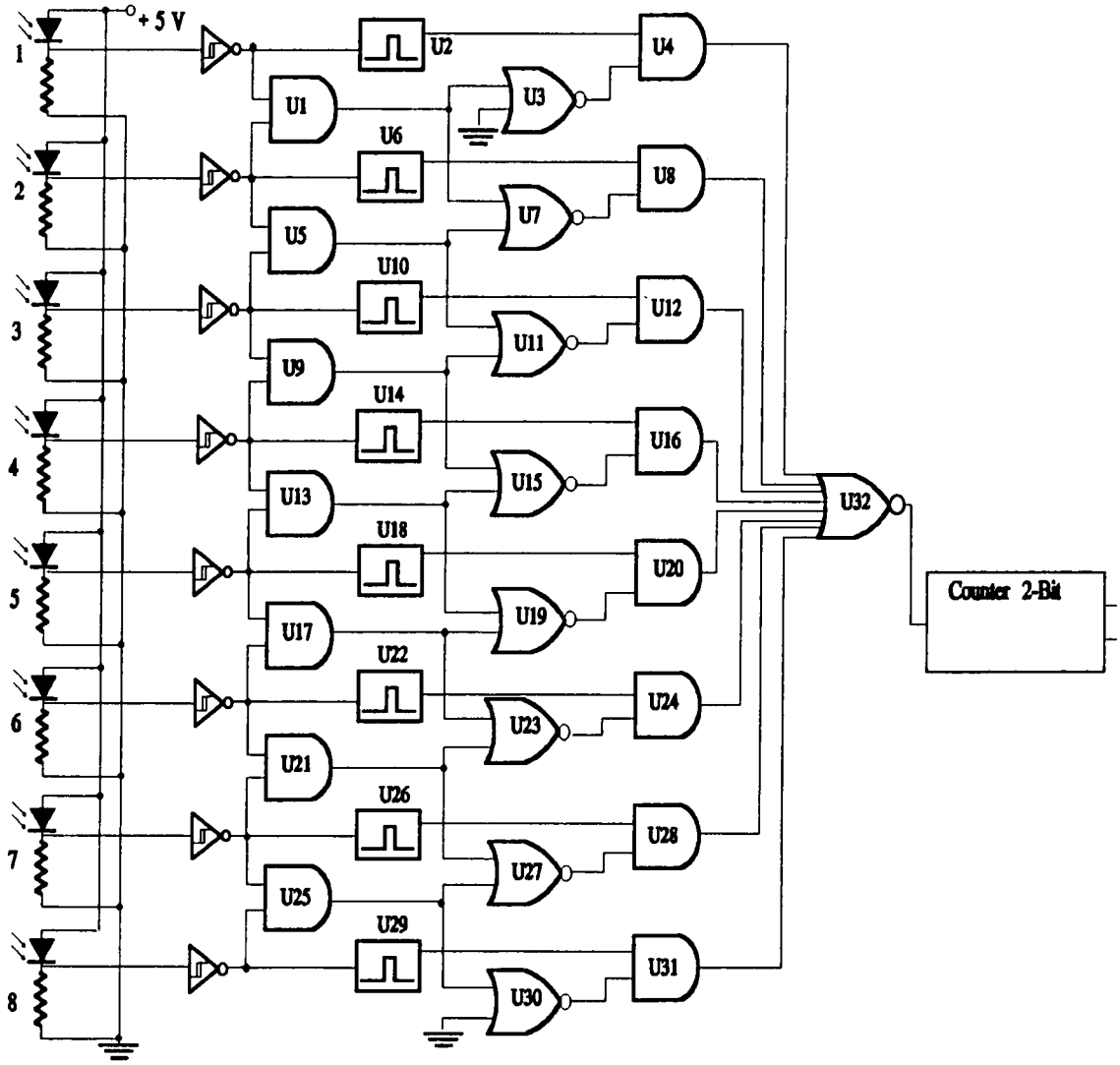


Figure 2-4 *Original asynchronous circuit.*

beam, then channel 3's logic would disable channel 4 from firing and so on. Thus, only one pulse from channel 1's one shot, U2, is allowed to pass through to an eight-input NOR-gate, U32, which was connected to a 2-bit counter. The result is that the 2-bit counter only increments once per pill, and other neighboring channels are prevented from being counted until that pill passes through the sensor region and the circuit returns to normal logic levels. Only then can another pulse be generated by these channels.

Four copies of the circuit shown in Figure 2-4 are required for the system (one for each array). The local 2-bit counter for each array acquires a subtotal count. This reduces the inputs to the system microcontroller from 32 to 8 input pins. The microcontroller monitors the state of the outputs of the 2-bit counters and keeps a running tally for each array in memory.

Note that channels separated by at least one other channel are not locked out and may produce pulses. This logic is designed to catch two different pills that may fall side-by-side but separated by at least one channel. Thus, this logic behavior does not require perfect single-file separation of objects by the handling system. This also means that odd-shaped objects that have protrusions (L or E shaped, etc.) or objects that have holes in the middle (washers, nuts, etc.) could not be detected and counted accurately. A single one of these odd-shaped objects could fall in a manner to trip two different separated channels resulting in an inaccurate double-count being generated. For pills, this is not a problem since all known pills are optically solid and geometrically elliptical or oval in shape with no odd protrusions.

In the event that two pills fell and interrupted two beams on widely separated channels at exactly the same instant, the net result is one total pulse. However, the pills must also fall at exactly the same speed and not be tumbling so that they interrupted the lower two arrays at exactly the same instant in time. By the time the pills fall into the lower two arrays, they are usually separated by enough vertical distance (and thus time) that two distinct pulses occur, resulting in a correct count. This assumes that each channel's one-shot has been adjusted to the same RC time constant. This requires closely matched components or adjustable components to give very uniform timing across all the channels. It is easy to see how this circuit is timing critical! Each one of the four circuits in Figure 2-4 occupied one large (8 in $\times$ 8 in) prototyping breadboard.

CHAPTER 3

DISCRETE LED-PT BEAM DESIGNS

This chapter describes how the asynchronous glue logic circuit presented in Chapter 2 was replaced and later improved by the use of complex programmable logic devices (CPLDs). The CPLDs had an immediate positive impact at reducing the associated circuitry and size of the sensor electronics. Testing, however, revealed previously undetected behavior of the free-falling pills that caused double counting to occur. As one problem was fixed, other problems became evident and were subsequently corrected in the design. Some improvements to the design were made by pulsing the LEDs, and these designs are also discussed. Ultimately, the methods here proved successful for objects down to a size of 2.5 mm, and many things were learned about the behavior of free-falling objects.

3.1 Constant IR Beam Designs

The first design using the CPLDs employed the existing sensor tube with its arrays of LED-PTs. The Schmitt triggers were retained to provide TTL levels and hysteresis. The remaining asynchronous glue logic was replaced with a synchronous design that provided sample memory to the data generated by the sensor. A schematic of one array's electronics is shown in Figure 3-1. The first version programmed into the CPLD supported one array of eight LEDs. The outputs of that array's Schmitt triggers were connected to the input/outout (I/O) pins of the CPLD. Each input was programmed to

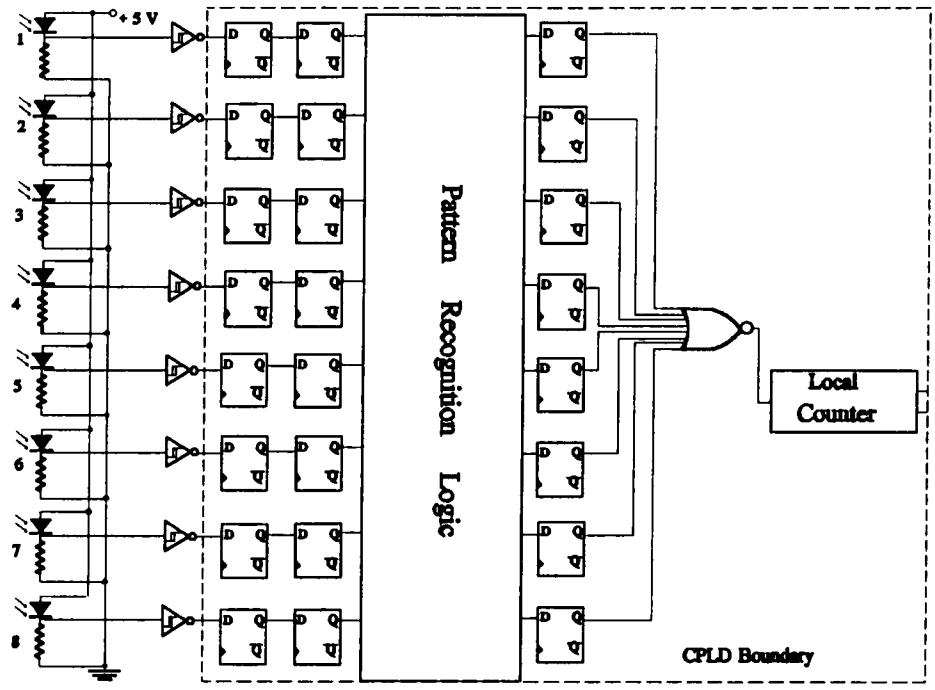


Figure 3-1 *Approximate schematic of the first synchronous CPLD design.*

connect to two D-type flip-flops connected in series. This allowed two discrete samples of data to be taken and analyzed.

The clock speed of the flip-flops was next determined. The pills pass through the upper two arrays at a speed of 110 cm/s and the lower two arrays at 150 cm/s. If a minimum pill thickness is 2.5 mm, then a pill of this thickness can be counted or "sampled" approximately four times by *each* array, with a clock speed of less than 1 MHz. The minimum pill thickness of 2.5 mm was set by the limit of how physically close the LED's and PT's holes in the sensor tube could be placed. A few pills are smaller that 2.5 mm for at least one of their dimensions. However, this did not appear to be a problem. If the probability of counting a pill that is smaller than the sensor

resolution is 0.95, then the probability of not counting, or missing, the pill is 0.5 for one array. For four arrays to miss the pill, the probability becomes $(0.05)^4$. Therefore, the probability of counting a pill with four arrays becomes $1 - (0.05)^4 = 0.99999375$. The microcontroller simply counts the four arrays separately as long as pills are falling through the sensor. When any of the counters are near the desired total, the microcontroller briefly stops the motors and compares the four counts and takes the highest number. This assumes that no double counts occur. This scheme works well for most pill sizes, but for pills smaller than the sensor spacing, problems occur as described later in the chapter.

Since the pills fall asynchronously with respect to the system clock, precaution must be taken to avoid metastability problems [8]. If an input does change during a clock edge, the output of the first flip-flop will be metastable for several nanoseconds and then settle to either a LOW or HIGH output state. Since any size pill can be counted several times because of the high sampling speed, the next clock period will provide a stable input, and the pill will be correctly detected. Thus, although the inputs to the CPLD occur asynchronously, metastability of the first flip-flops is of little concern.

To better understand the behavior of the Schmitt trigger outputs, a logic analyzer was used to monitor these signals. An example of the logic analyzer's display is shown in Figure 3-2. ONEs and ZEROs have been superimposed for clarity. These types of wave patterns were used to develop simulation input test vectors for software simulation. Various patterns of ONEs and ZEROs, representing sampled data from the first two rows of flip-flops, were used to test the programming before the chip was programmed.

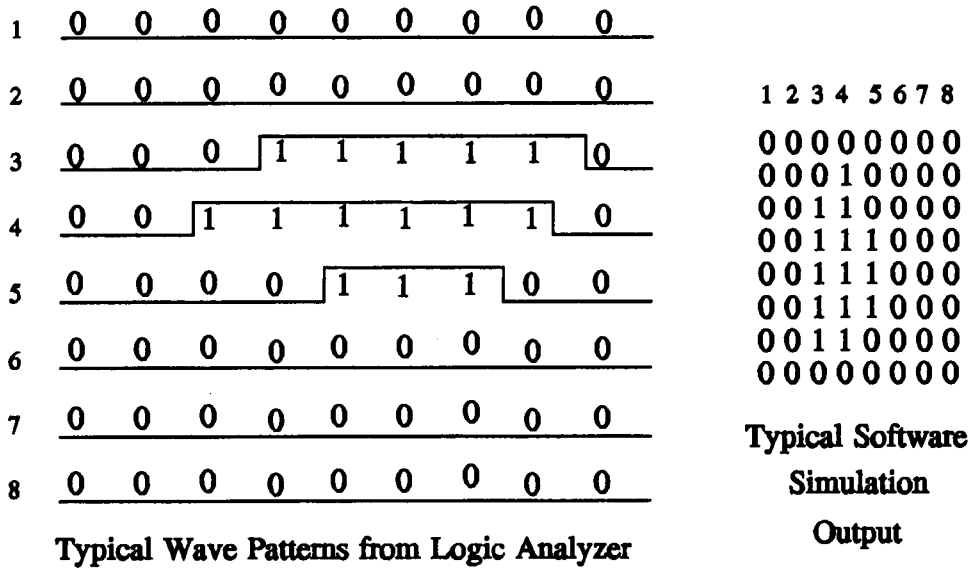


Figure 3-2 *Typical signal behavior from the sensors into the CPLD.*

3.2 Pattern Masks

Now that typical input data patterns could be modeled with the software simulation, a pattern recognition mask was developed to detect the falling pills [9]. The first pattern attempted was a T-shaped mask shown imposed over a sample of input test vectors in Figure 3-3. This mask, similar in function to the former asynchronous design, ignores activity on adjacent channels once a pill is detected. That is, if two pills fall together, they must be separated by at least one channel before two counts are generated. A third row of flip-flops was used to provide a pulse of one clock length to the NOR gate that monitors all eight channels for activity. The pattern recognition logic was implemented in combinatorial logic that determined the D-inputs to the fourth row of flip-flops. By changing the logic to rely on the present state of the first two flip-flops in any

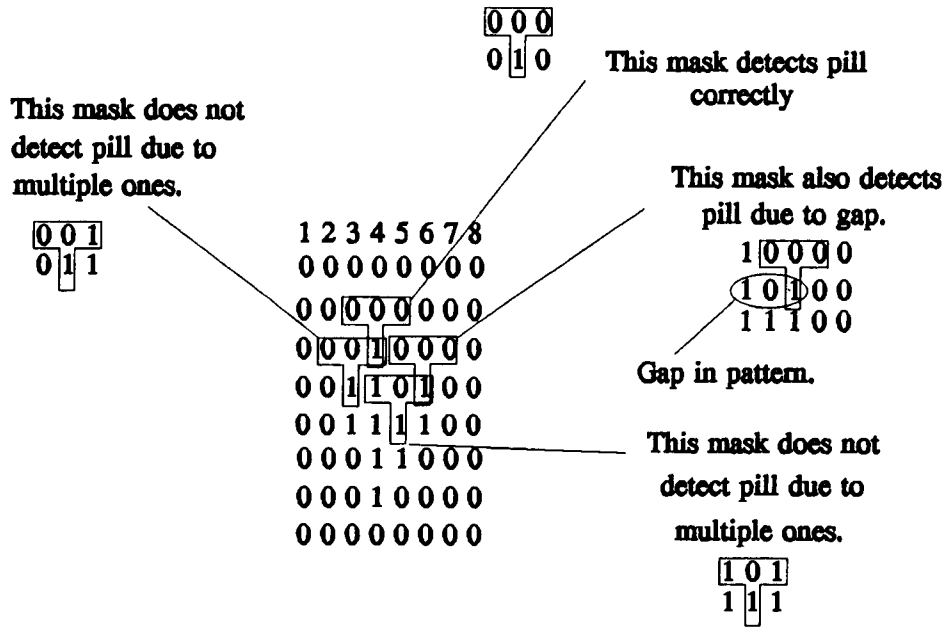


Figure 3-3 *Masks used to detect patterns.*

given channel and its neighboring channels, various pattern recognition "masks" were implemented.

The logic design and simulation vectors were entered into the computer using a hardware description language (HDL) called PALASM© from Advanced Micro-Devices (AMD) [10]. PALASM was one of the first HDLs and is widely used for smaller logic circuits such as the ones described here. Logic is entered in the form of boolean equations although higher forms of constructs such as CASE, IF-THEN-ELSE, and State Machine syntax are also supported. Figure 3-4 gives a few select equations from the source code used to implement the pattern recognition masks. The keyword NODE is used to access the second layer of buried logic in the MACH-210 part [11]. All flip-flop

```
;*********************************************************
;*  A PILL COUNTING DESIGN                               *
;*  Contains extra buffers to look three rows deep       *
;*********************************************************
;*********************************************************
;*                          INPUTS                       *
;*********************************************************
PIN 35  = CLK;
PIN  2  = INPUT1;
PIN  3  = INPUT2;
PIN  4  = INPUT3;
PIN  5  = INPUT4;
PIN  6  = INPUT5;
PIN 14  = INPUT6;
PIN 15  = INPUT7;
PIN 16  = INPUT8;
;*********************************************************
;*                         OUTPUTS                       *
;*********************************************************
PIN 20  = PULSE;
PIN 18  = COUNT0;
PIN 19  = COUNT1;
;*********************************************************
;*                          NODES                        *
;*********************************************************
NODE 94 = IN1_BUF1;
NODE 60 = IN1_BUF2;
NODE 53 = IN1_BUF3;
NODE 54 = IN1_BUF4;
NODE 56 = IN2_BUF1;
NODE 49 = IN2_BUF2;
;*********************************************************
;*              INPUT REGISTER EQUATIONS                 *
;*********************************************************
EQUATIONS
IN1_BUF[1..4].SETF        = GND;
IN1_BUF[1..4].RSTF        = GND;
IN1_BUF[1..4].CLKF        = CLK;
IN1_BUF[1] := INPUT1;
IN1_BUF[2] := IN1_BUF[1];
IN1_BUF[3] := IN1_BUF[2];
IN1_BUF[4] :=  IN1_BUF[1] * /IN1_BUF[2] * /IN1_BUF[3]
           *  /IN2_BUF[2] * /IN2_BUF[3]
           *  /IN3_BUF[2] * /IN3_BUF[3];

IN2_BUF[1..4].SETF   = GND;
IN2_BUF[1..4].RSTF   = GND;
IN2_BUF[1..4].CLKF   = CLK;
IN2_BUF[1] := INPUT2;
IN2_BUF[2] := IN2_BUF[1];
IN2_BUF[3] := IN2_BUF[2];
IN2_BUF[4] :=  IN2_BUF[1] * /IN2_BUF[2] * /IN2_BUF[3]
           *  /IN1_BUF[2] * /IN1_BUF[3]
           *  /IN3_BUF[2] * /IN3_BUF[3]
           *  /IN4_BUF[2] * /IN4_BUF[3];

PULSE.SETF         = GND;
PULSE.RSTF         = GND;
PULSE.CLKF         = CLK;
PULSE             :=   /IN1_BUF4 * /IN2_BUF4 *  /IN3_BUF4 *  /IN4_BUF4
                   *   /IN5_BUF4 * /IN6_BUF4 *  /IN7_BUF4 *  /IN8_BUF4;

COUNT[0..1].SETF   = GND;
COUNT[0..1].RSTF   = GND;
COUNT[0..1].CLKF   = CLK;
COUNT0         := /PULSE * /COUNT0              ;* x0 => x1 *
                   +  PULSE *  COUNT0;          ;* x1 => x1 *
COUNT1         := /PULSE * /COUNT1 *  COUNT0    ;* 01 => 10 *
                   +  PULSE *  COUNT1           ;* 10 => 10 *
                   + /PULSE *  COUNT1 * /COUNT0;  ;* 10 => 11 *
```

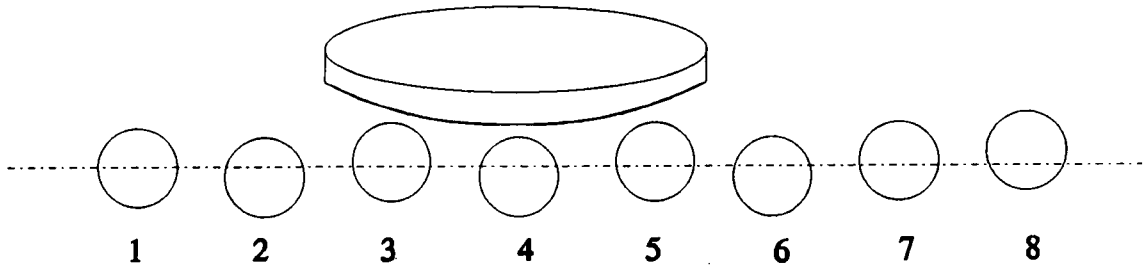
Figure 3-4 *Sample code of pattern recognition masks and 2-bit counter.*

elements are D-type by default and must have a clock defined. Asynchronous set and reset functions are banked within this particular chip and thus are used on a "global" basis. A ':=' is used to denote the input function to flip-flops, where combinatorial logic is denoted only by an ' = ' symbol.

3.3 Problems with Constant Beam Designs

When the CPLD was programmed with the T-shaped mask shown in Figure 3-3 and tested in the system, double counts still occurred but at a significantly lower rate of approximately 1 out of 50 chances. After repeated drops of one pill at a time, a double count was captured on the logic analyzer. The resultant pattern was similar to that also shown in Figure 3-3. The gap in the pattern resulted in two pulses, and thus two counts or a double count were generated for one pill.

Figure 3-5 shows how such a pattern might be generated and the modified-T mask that cured this problem. If a slight misalignment in the mounting of the IR-LEDs occurred, or their biasing intensity varied from one IR-LED to the next, two channels (for example 3 and 5) could change states one or two clock pulses before the middle channel (channel 4) changed. By extending the width of the T-shaped mask, the criterion for detecting two separate pills became that two channels of separation must appear between pills before two counts could be generated. Once the larger T-shaped mask was implemented and simulated, the part was reprogrammed. This new version was capable of handling 16 inputs (two arrays) in one chip. Thus, two small CPLDs could support all four sensor arrays. This new version produced counts of 100% accuaracy for quantites



1	2	3	4	5	6	7	8
0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0
0	0	1	0	1	0	0	0
0	0	1	1	1	0	0	0
0	0	1	1	1	0	0	0

Figure 3-5 *Uneven lighting error*

as high as 2000 pills for all pills larger than 2.5 mm. However, smaller size pills with at least one dimension less than 2.5 mm gave erroneous counts that were both over and under the actual amount. Before formal testing and data collection was performed on this design, an attempt was made to resolve the over and under count errors.

Two problems were identified that caused these errors. First, the over counts were because of double counts. After many attempts of dropping one pill at a time, one of these double counts was captured on the logic analyzer. A sample wave form showing this double count is shown in Figure 3-6. This figure also shows the most probable cause of the time gap in the waves. A small, thin, flat pill could fall so that it interrupts one beam momentarily, then moves in between the two beams (resulting in sampled ZEROs),

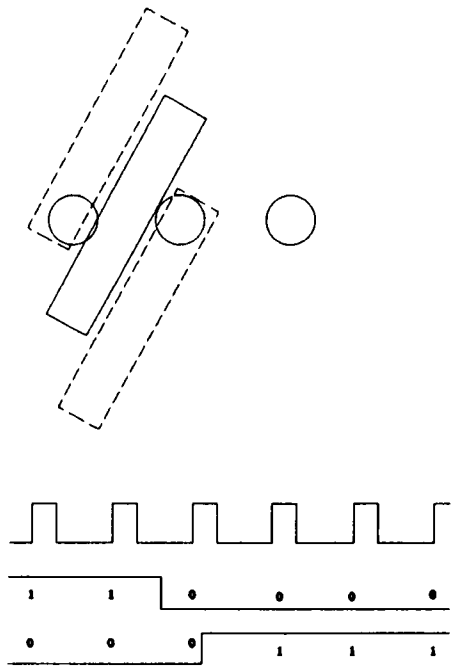


Figure 3-6 *Double count error.*

and later breaks an adjacent beam. Notice that this wave pattern is nearly identical to one caused by two pills closely "chasing" each other down the sensor tube.

To detect this event, the mask was modified by adding another row of D-type flip-flops to the input signals, making a total of four flip-flops per channel. The top of the wide T-mask was then "thickened" to two rows of data. Now when a pill falls through and is counted, no other pill may be counted until two rows of ZEROs have been sampled. This guarantees that at least one clock period must occur between two pills (or the error of one pill and two input pulses) before a second count is generated. Thus the clock rate can be adjusted to set the physical separation that must occur between pills. Slower clock speeds yields lower sampling speeds and result in the resolution of any one

array being reduced. The redundancy of four sensor arrays decreases the probability of a pill going undetected. The CPLDs were programmed again and tested in the circuit with no over count errors detected. However, under count errors increased because of the reduced sampling speed of ~ 50 passes/s. Also the addition of the extra flip-flop for each input resulted in a design that would not place-and-route in two MACH-210s. Hence, four MACH-210s were needed, one for each array. The device utilization percentage in each device was less than 60%. Thus, if future needs necessitate changes in the MACH-210, resources exist in the chips to add to or modify the logic without changing the pin-out of the chips or the printed circuit board on which they will be mounted. Also the design can be redone in one of the larger MACH family members.

3.4 Pulsed Designs

The second reason for inaccurate counts, specifically under counting or missing objects, stemmed from nonparallel light in the sensor coverage area. The LEDs from neighboring channels were eliminating shadows, and objects were being missed. One solution to interference of LEDs from neighboring channels is to use a pulsed system. In this system only one LED is turned on at a time. During this time the state of that LED's corresponding PT is examined to determine the presence of an object. All the LEDs are pulsed one at a time in sequence until all the LED-PT pairs have "covered" the opening of the tube. By storing the results of more than one pass before a decision is made to generate a count, missed object errors can be lessened if not eliminated altogether.

A block diagram of a pulsed LED system is shown in Figure 3-7. To pulse the LEDs, the CPLD logic started a logic "1" (as the ON bit) in a shift register. As the ON bit moved along the length of the register, each LED would light. The inputs from the PT sensors were examined only during the respective ON-state for that channel. When a channel was in an OFF-state, the input logic held the value of its present state. Pulsing all the channels is referred to as making one sweep or pass of the sensor tube. Four sample passes were used to collect the same amount of data as the four rows of flip-flops in the previous design. The input logic was configured so that once an object was detected, the logic level was held constant until the end of four passes. This logic

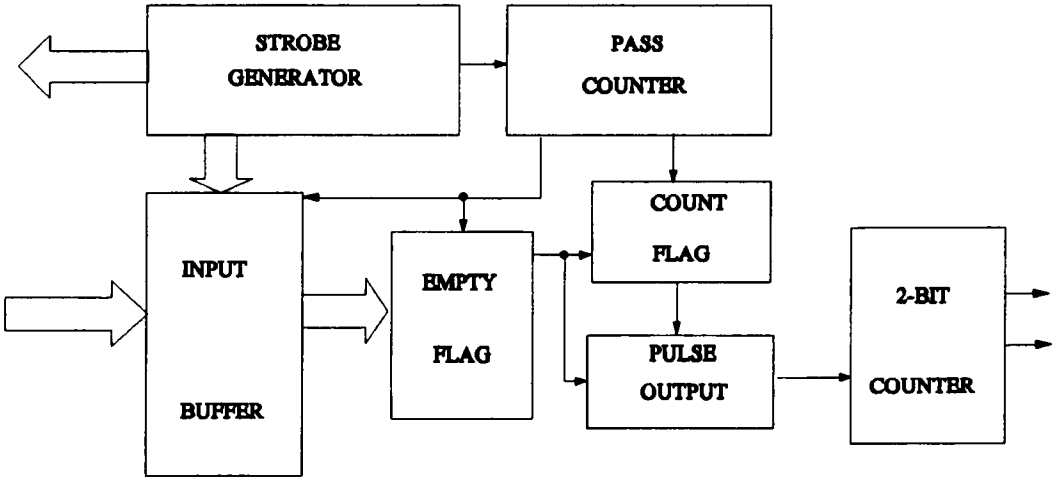


Figure 3-7 *Strobed LED system block diagram.*

behavior is similar to a set-reset flip-flop or latch and provides a debounce effect to the input signals. During the four passes, if an object is detected, an empty flag is set FALSE. At this point a count is *not* generated, but the change in state of the empty flag acts as an arming mechanism. At the end of the fourth pass, the empty flag is examined. If an object is present, the empty flag is FALSE. This causes the count flag to be set TRUE. At this point a pulse is generated which increments the 2-bit counter. The input buffers (or latches) and the empty flag are synchronously cleared after being examined. Then four more passes begin. The count flag remains TRUE until the object has passed through the sensor array. No further incrementing of the 2-bit counter is allowed until four passes are made and no object is detected. When the empty flag is examined after a set of four passes and the sensor tube is found to be empty, the count flag is released, and the circuit waits for the next object to enter the sensor region.

The above scheme was tested for one 8-LED-PT channel sensor array. The next step involved designing a circuit board for a four array sensor tube. The design was actually four small circuit boards assembled to form a single tube-shaped assembly around the actual tube through which the objects fall. The small assembly contained a 5 V regulator with filter capacitors, one MACH-210, Schmitt triggers, and line drivers for driving the LEDs. It was found that instead of strobing one channel at a time, two channels could be pulsed and evaluated at once if they were separated by at at least three other channels. This reduced the logic greatly and allowed all the logic to fit into only one MACH-210.

3.5 Results of the Pulsed Designs

The blind zones where objects were missed because of nonparallel light were eliminated. For pills larger than 2.5 mm, counts with one array proved perfect for as many as 3000 pills. The pulsed designs still had the problem of sensor spacing and small pills causing double counts at higher sampling rates (>1000 passes/s). Lowering the sampling rate reduced the double counts but increased the pills that were missed by the sensor, resulting in under count errors.

When the individual arrays were assembled around the sensor tube, other problems were encountered. The light from the X-direction LEDs interfered with the PT of the Y-direction array for both the top and bottom sets of sensors. To solve this, two arrays were disabled, the X-direction at the bottom and the Y-direction at the top. This brought good results with 100% accurate counts being achieved for pills larger than 2.5 mm. At this point, testing was stopped since it was obvious that sampling individual sensors and using count memory flags was the method to pursue. The only problem now was to find a way to increase sensor density to prevent the troublesome double counts and allow a higher sampling rate to eliminate missed pills.

CHAPTER 4

PIXEL ARRAY DESIGNS

Figure 4-1 shows the block diagram of the present system. To solve the problems with sensor spacing, a pixel array optical sensor chip was obtained. This chip contains pixels placed closely enough that no pill is able to get in between two pixels and cause double counts. The data out of the array are in the form of discrete periods of analog voltages that are clocked out in serial fashion. Filtering was needed to eliminate the switching noise between samples, and threshold detection was needed beyond the standard Schmitt trigger. Once the data were converted to a useful TTL level, the pattern recognition algorithm had to be changed to handle the serial data. The pulsed LED

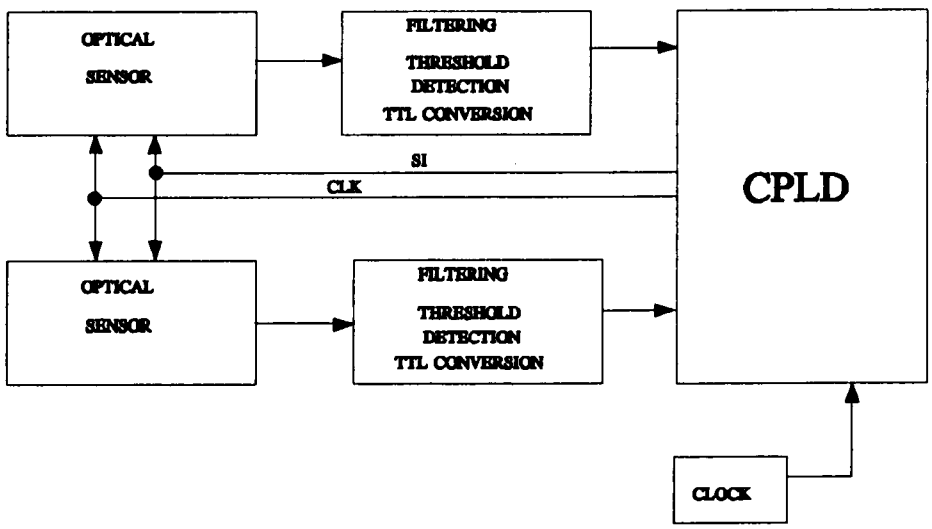


Figure 4-1 *Block diagram of pixel strip system.*

scheme was replaced by a single constantly on LED and lens to provide parallel light. The following sections give more details on each block.

4.1 Operation of the Pixel Array Chip

The pixel strip chip shown in Figure 4-2 has a 1 × 128 strip of optically sensitive pixels. The pixels measure 120 × 70 μm with 125-μm center-to-center spacing. Control of the chip is simplified by internal logic requiring only a read out clock (CLK) and start-integration-pulse (SI) signal. The chip may be readout in serial mode or in parallel mode in blocks of 64 pixels. The serial configuration is used in this design. When the external SI pulse is applied to the chip, the first 64 pixels are clocked out in synchronization with the CLK signal. The chip produces a SO1 pulse output that is connected directly to the SI2 input and starts the 65th pixel on the next rising edge of CLK. The analog outputs

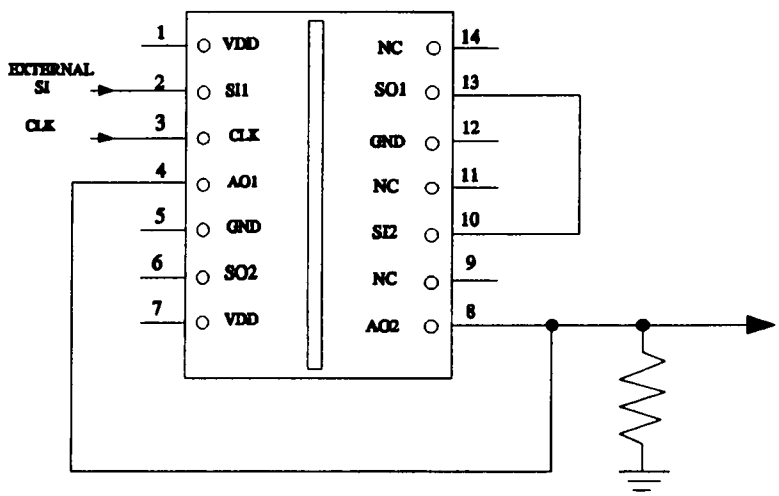


Figure 4-2 *Pixel strip optical sensor chip.*

AO1 and AO2 are tied together into a common load resistor. The CLK signal can be any frequency between 10 and 500 kHz. The recommended integration time is 5 ms but varies as a function of LED intensity. The recommended wavelength of the LED is 750 nm [12].

After the SI pulse is applied, the first discrete analog sample appears at AO1 (or AO2) less than 1 μs after the rising edge of the serial clock. The voltage at AO1 stays valid for the HIGH and LOW state of the clock. As expected, there are switching spikes between samples as the different pixel values are clocked out of the chip. A simple RC low-pass filter with a corner frequency of ~338 kHz was added after the load resistor to reduce this noise.

4.2 Threshold Detection Circuits

Figure 4-3 shows a typical pair of waveforms that one might see if viewing the discrete analog samples from the output of the pixel array chip and the step change in threshold level of the threshold detection circuit while an object is in the sensor's view. The threshold detection circuit was designed to provide a well-behaved square pulse that is accurately representative of the large dip in the analog samples. This rather smooth dip occurs when an object is well into the sensor's view. However, when the edge of an object first falls into view of the sensor, the analog samples have many small dips that often appear as a heavily distorted random sinusoid waveform. The many small dips are caused by the irregularities in the edge of the falling object and the scattering of light around the edges of the object.

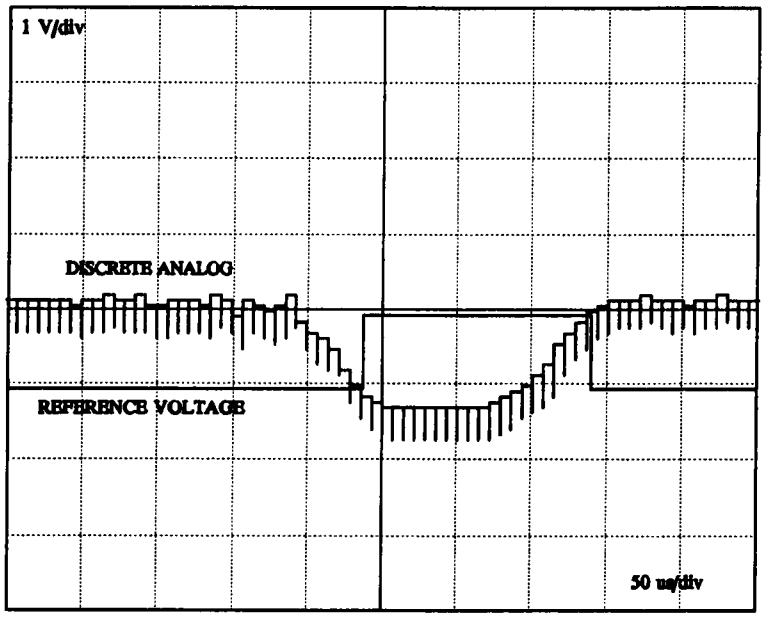


Figure 4-3 *Typical oscilloscope screen of discrete analog samples and output pulse of threshold detection circuit with hysteresis.*

To avoid counting these pulses as many individual objects, hysteresis was needed. Normally, a standard Schmitt trigger device works fine, but the output voltage of the pixel array chip was not sufficient to be detected by a Schmitt trigger. To detect the range of voltages present from the pixel array chip, a standard LM393 comparator chip was used. The circuit is shown in Figure 4-4. Potentiometer R1 provides a voltage divider that establishes a reference voltage (VREF) on the positive input to the LM393. Feedback resistor (RF) is used to change VREF as a function of the output voltage (VOUT), which in turn is controlled by the input voltage (VIN). R1 is adjusted so that VREF is well below VIN, resulting in a VOUT near zero volts. For a first-order approximation, it is

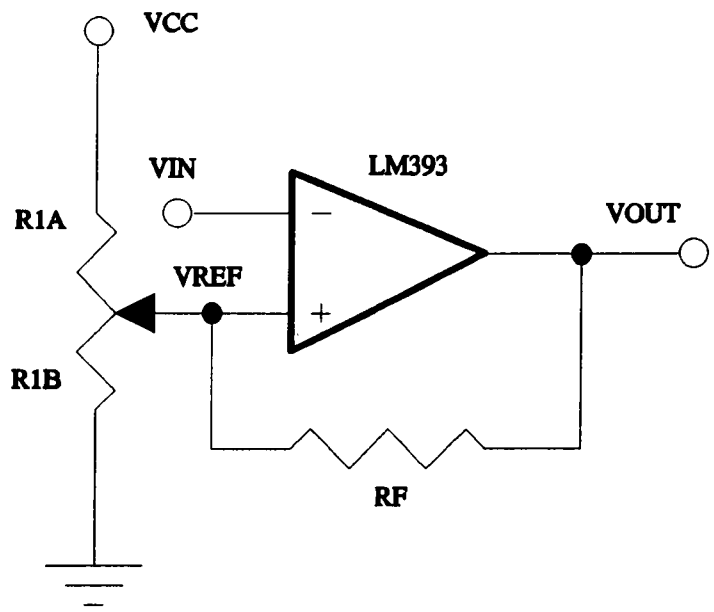


Figure 4-4 *Comparator circuit with hysteresis used for threshold detection.*

convenient to consider RF in parallel with R1B in calculating VREF. In fact, RF lowers VREF from the voltage given by R1 alone.

When VIN drops just below VREF, VOUT switches to a voltage approximately equal to VCC. Now RF is parallel with R1A, again to first-order approximation, raising VREF to a new higher voltage. Now VIN must return to near its normally higher voltage before VOUT will toggle back to its normally LOW state. This positive feedback establishes the hysteresis need to eliminate most bounce in VOUT that is caused by small voltage fluctuations of VIN near VREF [13].

4.3 Characterization of the Object's Behavior

The control signals for the pixel array chip were programmed into the CPLD and a prototype circuit was constructed to test the functionality of the pixel array chip, filter, and threshold detection circuit. A clear plasic tube was used to guide the dropped pills. A lens was mounted on the outside of the tube opposite the pixel array chip. An LED was positioned at the correct focal length to give parallel light in the tube. A logic analyzer was used to view the output of the comparator as pills were dropped one at time and the behavior of the circuit was observed.

Despite the threshold detection and hysteresis provided by the analog filtering, the data still appeared with many pulses generated by a single pill. An ensemble of waveforms that shows this behavior is shown in Figure 4-5. Each line repesents one pass of the sensor array. The lines are numbered, and reduntant lines (lines 5—11) are omitted. The short pulses that frame the larger pulse in lines 1 and 2 are because of light scattering off the edge of the chip as it first enters the view of the pixel array. The manner in which the pixel array chip is controlled makes it sensitve to this problem. Specifically, this is because of the high sampling rate used in the pixel array, relative to the speed of the falling objects. The pixels do not have time to fully recover between passes. Thus the new arrival of a shadow on the sensor combined with the residual charge left in the pixel results in fluctuations of some samples that are sufficient enough to trip the threshold detection comparator, resulting in the narrow pulses. Notice that after several passes the pulse eventually appears solid (as in lines 4—12). To avoid generation of double counts, a digital filter was needed to pass only the larger pulses.

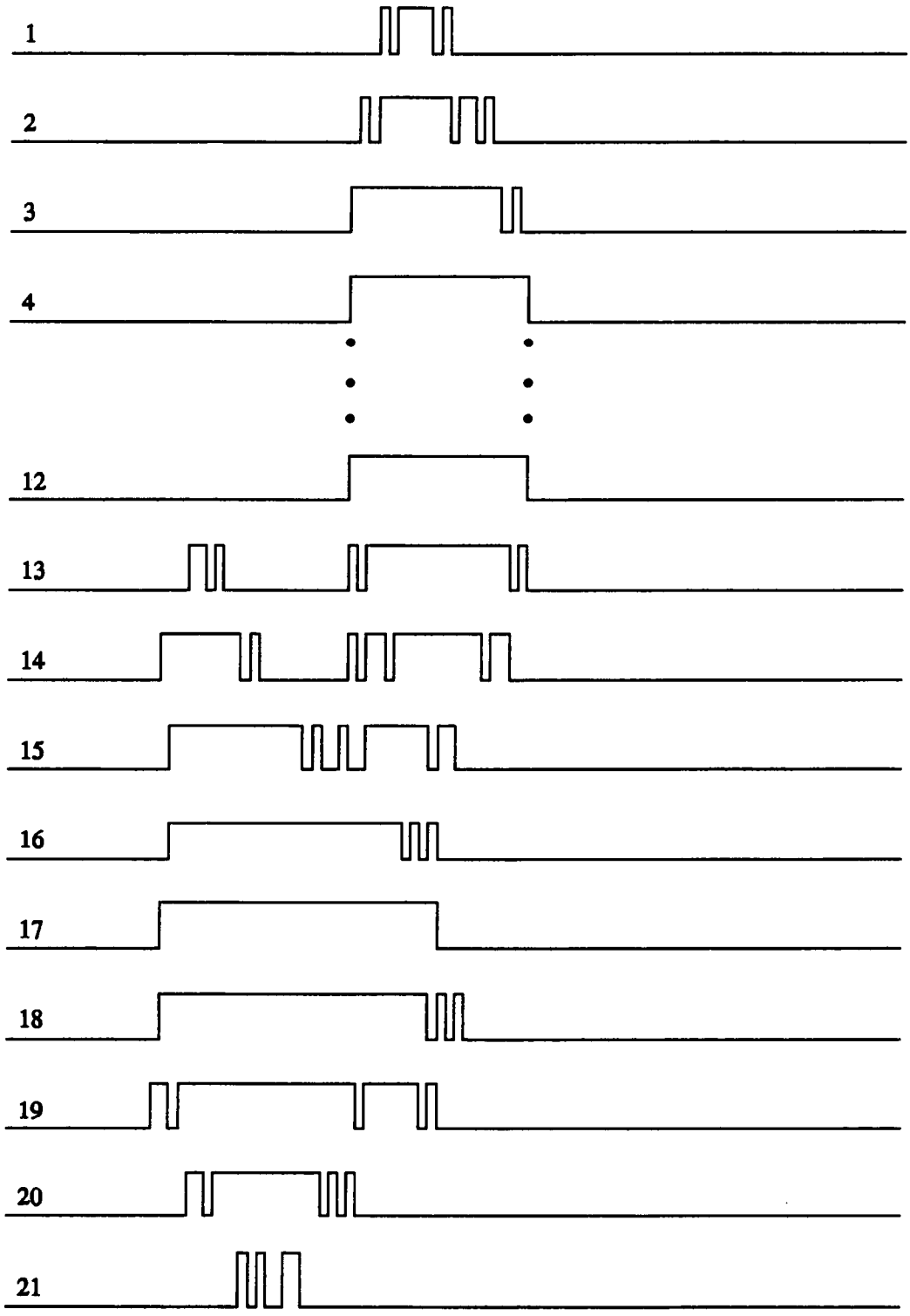


Figure 4-5 *Typical ensemble of waveforms from the threshold detection circuit.*

This filter must also be able to discern between the smaller noise pulses and the arrival of a second object (shown in lines 13—15). This is the pattern typically caused by two objects in the sensor's view at the same time. This pattern can also be generated by dropping an odd-shaped object or an object with a transparent region such as a washer or nut. If these types of objects are to be counted in a system like this, then they must fall in perfect single-file fashion so that the pattern recognition algorithm sees a period of no activity between the falling objects. Fortunately, every known type of pill is solid or at least opaque in appearance and with the exception of the light-scattering problem, never generates two pulses with this pixel array sensor. This proved very fortunate in that now a recognition system could be designed to detect two pills falling side by side but separated by some finite distance. Pills that fall in each other's shadow in one direction will hopefully be seen as two pills by the second sensor (as discussed in Chapter 3), which is orientented at a 90° angle and placed ~5 cm below the first center. As the pills tumble down the sensor tube, they will usually separate and be counted by one of the two sensor arrays. In the event that two pills touch each other as they pass through both arrays so that no dicernable break occurs in their shadow, they are counted as one pill.

4.4 Pattern Recognition Logic Design

Once the input behavior of the falling objects had been characterized, the pattern recognition logic was designed. The logic once again was programmed into a small CPLD. A system clock of 1 MHz was used as the base frequency for all the CPLD logic. This clock was divided by four to provide a 250-kHz sample clock to the pixel array chip

to read each pixel. The 1 MHz system clock provided intermediate clock edges for the logic to perform various functions between the arrival of samples.

The block diagram of one channel of object detection logic is shown in Figure 4-6. Logic pulses arrive in a synchronous but random logic level manner as shown in Figure 4-5 and are stored in the sample buffer. This buffer is a serial string of flip-flops that are clocked from the system clock but only advance the data during the sample clock.

Since only one edge of the pill must be detected to generate a count, all 128 samples are not required to be stored prior to evaluation. Instead, a digital low-pass filter was designed to consider enough samples to eliminate narrow pulses caused by light scattering. The filter used the output of the serial string flip-flops and looks for consecutive strings of logic ONEs and ZEROs before changing states. Thus, periods of time where the input samples are changing states rapidly are ignored by the filter. Several different lengths of shift registers were programmed and tested, and the results are given in Chapter 5. The output of the digital filter is a well-behaved pulse with all glitches removed.

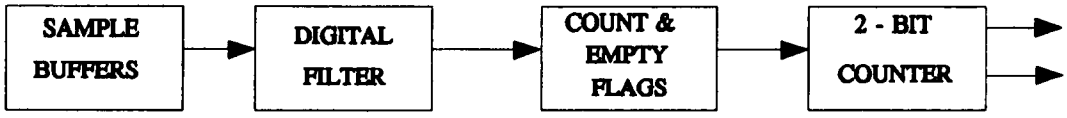


Figure 4-6 *Block diagram of one detection channel.*

This filter output is then evaluated by the count-flag and empty-flag logic. The simplest configuration of counting logic has one count-flag and one empty-flag per sensor channel. The count-flag is set TRUE whenever the filter output indicates that an edge has been detected. If this is the first edge detected the normally TRUE empty-flag is set FALSE one system clock period later. One system-clock-wide pulse is produced whenever the count-flag and empty flags are both TRUE. This pulse is used to increment the local 2-bit counter. The count-flag and empty-flag logic levels are held until the end of the pass (or reading) of all 128 pixels. Just before the start of the next pass, the count-flag is reset. The empty-flag is only reset if the count-flag is FALSE, indicating that no edge was detected during the past sensor pass and the sensor region is now empty of any objects. As a pill falls through the sensor area, it is detected by many passes. The exact number of passes is a function of the pill's size and speed. Regardless of the number of passes made, the count-flag goes TRUE whenever one edge is detected during a pass and gets reset after *each* pass. The empty-flag *remains* FALSE until one complete pass is made with *no* object detected. This allows only one increment of the 2-bit counter per pill and is referred to as single-file mode of operation.

A more elaborate configuration uses multiple count-flags and empty-flags for each channel. The extra levels are used to detect multiple objects that fall into the sensor region together. This configuration is desirable in that it eases the burden on the mechanical handling system to provide perfect single-file separation of the objects. Figure 4-5 illustrates the input pulses that might occur as a second object enters the sensor region

before the first objects has exited. For this pill counting system, a second layer of count-flags and empty-flags was added to detect two separated objects within a single scan. The second layer is obviously dependent on the state of the first layer and only activates once the first layer count-flag is TRUE. Thus the first layer counts the first edge, and thesecond layer counts the second edge. Because of the width of the digital filter, the two objects must be separated enough that two distinct pulses are produced by the filter. Objects that fall closely together are only detected as one pill. One could easily extend this configuration to a third or fourth layer if needed provided there was room to fit the extra logic into the CPLD.

Once again, the counter was designed to be 2 bits in size to interface to the present microcontroller in the system. The number of bits can easily be changed as needed by simply reprogramming the CPLD. After the design was programmed into the CPLD, the circuit was assembled on a breadboard and tested with several different size pills.

The results revealed that the intensity of the LED and the adjustment of the threshold level were crucial to the accurate counting of objects. If the LED was too bright or the threshold level was too low, then blind spots in the sensor region caused counting errors. Smaller sized pills fell completely through the blind spots and were missed or they tumbled into and out of a blind spot, resulting in a double count. Once the levels were adjusted correctly, tests revealed the logic worked as designed and proved accurate enough to proceed with the construction of a more durable prototype to be used in more thorough testing of the mechanical mounting of the LEDs.

After testing the breadboard version of the circuit, a prototype board was made that contained two sensor chips. A clear plastic tube was attached to the board, and lens were mounted on the outside of the tube. At this point Dr. Speckhart experimented with the mechanical mountings for the LEDs at the correct focal length. Various LEDs were tried, and each was tested at different intensities. The mechanical design for the boards was then completed, and schematics were redrawn to develop another four-board tube-like assembly. These boards were then made and populated with components. The assembly was then tested and adjusted and then retested many times. Improvements to the digital filtering as well as the analog filtering and threshold detection were made.

At this point Dr. Speckhart proceeded with the design of the housing for the system. John Wilson also made changes to the microcontroller programming to provide additonal features. The empty-flags were monitored by the microcontroller as a built-in-self-test indicator. If the LEDs are not working or the tube is blocked by some object, then the empty-flag will be FALSE at powerup and an error message can be displayed.

CHAPTER 5

RESULTS AND SUMMARY

This chapter gives the results of testing many different-size pills in the prototype system. A summary of the work presented in this thesis is also included. Future work and recommendations for improving the design concludes the chapter.

5.1 Testing Methods

To test the accuracy of the counting system, the four-circuit-board tubular assembly was mounted inside a partial prototype housing of the pill handling machine. Three different-sized tablets and three different-sized capsules were chosen to test the system. These six different pills are representative of most common-size pills. Before testing began, the system was calibrated by dropping pills and adjusting the LED intensity and the level of the threshold detector. Several pills were counted, and readjustments were made until the optimum combination was found.

At this point it should be noted that the final housing prototype was still being fabricated. A partial prototype housing was available, but the proper mounting hardware for attaching the counting system was not designed. The counting system was attached with a combination of screws and hot glue to the underside of the system by Dr. Speckhart. The lenses were mounted to the side of the clear counting tube with hot glue. Thin strings of glue or scratches can be seen on the lens and are visible when the analog samples are viewed on an oscilloscope. Since the samples are from pixels placed 125 μm

center-to-center, even small scratches or foreign objects show up in the output of the pixel array chip. These shadows have a greater effect as the LED intensity is reduced. However, increasing the intensity of the LED decreases the sensitivity to smaller objects creating blind spots, as discussed in the previous chapters. If the threshold level is adjusted up to a higher level (~ 2.7 V), then the foreign object's shadow can cause a pulse that is sometimes wider than the digital filter's width. This does not occur as a constant interference but instead tends to occur if a pill falls within 10—20 pixels of the interference. It was also noted that the prototype circuit boards that were assembled into a tube-shaped assembly were the wrong dimension, resulting in the LEDs being mounted at the wrong focal length. This was corrected by not mounting the LEDs completely against the circuit boards. Instead, the legs of the LEDs were left approximately 5 mm longer. This extended the LED toward the lens and established the correct focal length, but the assembly was optically very fragile.

5.2 Results of Single-File Mode Testing

Despite the problems with the mounting of the electronics, some thorough testing was accomplished. The first configuration tested was a CPLD version that contained one count-flag and one empty-flag per channel. This configuration requires that objects fall in single file through the sensor area. For this system the LED intensity can be increased to minimize the shadows of foreign objects, and the threshold level can be adjusted to a point just below these shadows. With this calibration, any object that falls through will cause the analog samples to dip below the threshold, and the CPLD will count only the

first pulse seen during the scan. No further increments of the counter are allowed until one complete scan with no object detected occurs. This configuration gives the most assurance of no double counts being generated. If two (or more) pills fall through together so that no empty pass occurs between them, they will be counted as one pill, and the count displayed will be under the actual total. However, this must occur for both sensors, since the microcontroller will take the higher of the local counts.

The pills were counted in sets of 100. At this point the counts for both the top and bottom sensor were noted. (The top and bottom pulse signals are available as test points and used to increment two test counter displays that are not part of the normal system. The operator of the pill counting system only sees the higher value of the two counts.) Table 5-1 shows the results of the six different types of pills counted. Occurrences where two pills managed to stay close enough to be counted as one pill by both sensors are shown in bold. Notice, there are single occurrences where either the top or bottom counters detected only 99 pills while the other sensor detected 100. Since the microcontroller takes the larger of the two counts, no under count error occurred. This is evidence that the multilevel sensor scheme works and is a worthwhile feature of the system. It is odd to note that the medium size pills seem to be harder to detect than the smaller or larger pill sizes. It was observed during testing that the handling system had a bit more trouble separating these sizes. The parameters of the handling system that cause the pills to separate are programmable, and with little more adjustment by Dr. Speckhart and John Wilson, the degree of separation and thus the degree of accuracy will improve.

Table 5-1 *Test results for single-file version CPLD*

	TABLETS						CAPSULES					
	SMALL D 8 mm x H 4 mm		MEDIUM D 11 mm x H 5 mm		LARGE D 14 mm x H 8 mm		SMALL D 6 mm x L 17 mm		MEDIUM D 7 mm x L 20 mm		LARGE D 8 mm x L 22 mm	
Test	Top	Bot.	Top	Bot.	Top	Bot.	Top	Bot.	Top	Bot.	Top	Bot
1	100	100	99	100	100	100	99	100	100	99	100	100
2	100	100	**99**	**99**	100	99	100	100	100	100	100	100
3	99	100	100	100	100	100	100	100	99	100	99	100
4	100	100	100	100	99	100	99	100	99	100	100	100
5	100	99	**99**	**99**	100	100	100	99	100	100	100	100
6	99	100	100	100	100	100	100	100	100	99	100	100
7	100	100	99	100	100	100	**99**	**99**	100	100	100	100
8	100	100	100	100	**99**	**99**	100	100	100	100	100	100
9	100	100	99	100	100	100	100	100	**98**	**98**	100	100
10	**99**	**99**	100	99	100	100	100	100	99	100	**99**	**99**
Tot.	999 / 1000		998 / 1000		999 / 1000		999 / 1000		998 / 1000		999 /1000	

5.3 Results of Side-By-Side Mode Testing

The testing of the side-by-side mode versions of the CPLD did not go quite as well at the single-file mode testing. However, the data illustrate several key issues that will need to be addressed before the system is finalized. Two separate versions of the side-by-side mode CPLDs were tested, each differing in the size of the digital filter. The first version tested contained a filter 4 bits wide. This version was tested at two different threshold settings. The results are shown in Tables 5-2 and 5-3. At first glance, Table 5-2 seems to indicate that the sensitivity of the bottom sensor was adjusted too low since it detects only ~60% of the small tablets. It also occasionally generated a double count error, as shown in the medium tablets and small capsules. Larger pills were not attempted because of the poor results with the small and medium sizes. In general, the larger pills cast larger shadows and are easier to detect over a wider range of LED intensities and threshold voltages. It is pointless to test these until the problems with the smaller pills are corrected.

Table 5-3 shows the results of increasing the threshold voltage to 2.0 V for both sensors. Both sensors improved for the small tablets, but double count errors increased for the remaining sizes. It is obvious that blind spots in the sensor region occurred because of the high LED intensity. LED intensity could not be reduced because of the foreign object interference mentioned earlier. A third threshold level of 2.4 V was briefly attempted, but the errors were greater than 8%. Therefore, testing at that particular setting was abandoned.

Table 5-2 *Test results for side-by-side version CPLD with 4 bit filter and threshold level adjusted to 1.8 V*

	TABLETS				CAPSULES			
	SMALL D 8 mm x H 4 mm		MEDIUM D 11 mm x H 5 mm		SMALL D 6 mm x L 17 mm		MEDIUM D 7 mm x L 20 mm	
Test	Top	Bot.	Top	Bot.	Top	Bot.	Top	Bot.
1	93	59	100	98	100	102	98	99
2	95	45	100	100	100	100	100	100
3	94	63	100	101	100	100	100	101
4	90	65	100	100	100	101	99	99
Tot.	372 / 400		401 / 400		403 / 400		399 / 400	

Table 5-3 *Test results for side-by-side version CPLD with 4-bit filter and threshold level adjusted to 2.1 V*

	TABLETS				CAPSULES			
	SMALL D 8 mm x H 4 mm		MEDIUM D 11 mm x H 5 mm		SMALL D 6 mm x L 17 mm		MEDIUM D 7 mm x L 20 mm	
Test	Top	Bot.	Top	Bot.	Top	Bot.	Top	Bot.
1	98	86	102	103	102	106	98	102
2	99	84	99	104	100	105	99	104
3	100	83	101	102	102	107	100	103
4	99	83	103	102	100	105	102	106
Tot.	396 / 400		412 / 400		423 / 400		415 / 400	

The second version of the side-by-side CPLD was programmed with a larger digital filter of 7 bits. This version was also tested at two different threshold levels, and the results are shown in Tables 5-4 and 5-5. The extra bits in the filter allowed for higher threshold levels to be used to improve the accuracy. In fact, lower threshold voltages were briefly tested, but the system was too insensitive to smaller pills. Table 5-4 illustrates 100% accuracy for medium tablets, small capsules, and medium capsules. Again, it appears that the bottom sensor is a slightly insensitive to smaller pills.

The threshold level was increased to correct the insensitivity of the sensors, and the results are shown in Table 5-5. A slight improvement is seen in the top sensor. The bottom sensor improved for small tablets but was overly sensitive to noise pulses caused by light scattering or foreign objects, as indicated by the double count errors in the small and medium capsules.

5.4 Flow Rate and Small-Size Testing

The flow rate at which testing was performed varied with the size of the pill being counted. In general, the range was approximately 5—15 pills/s. Some pills cannot be handled too quickly or they crumble around the edges. If a large enough piece (size, > 0.8 mm) breaks loose in the handling system and falls through the tube, then it will be counted resulting in an over count error. Thus, speed testing in general is not necessary since the machine is not designed to handle pills greater than 15 pills/s. However, the

Table 5-4 *Test results for side-by-side version CPLD with 7-bit filter and threshold level adjusted to 2.0 V*

TABLETS					CAPSULES			
	SMALL D 8 mm x H 4 mm		MEDIUM D 11 mm x H 5 mm		SMALL D 6 mm x L 17 mm		MEDIUM D 7 mm x L 20 mm	
Test	Top	Bot.	Top	Bot.	Top	Bot.	Top	Bot.
1	100	91	99	100	100	100	100	100
2	98	84	100	100	100	100	99	100
3	100	88	100	100	100	100	99	100
4	99	83	100	100	100	100	100	99
Tot.	397 / 400		400 / 400		400 / 400		400 / 400	

Table 5-5 *Test results for side-by-side version CPLD with 7-bit filter and threshold level adjusted to 2.4 V*

TABLETS					CAPSULES			
	SMALL D 8 mm x H 4 mm		MEDIUM D 11 mm x H 5 mm		SMALL D 6 mm x L 17 mm		MEDIUM D 7 mm x L 20 mm	
Test	Top	Bot.	Top	Bot.	Top	Bot.	Top	Bot.
1	98	96	100	100	100	100	99	100
2	99	92	100	100	100	101	100	100
3	100	96	100	100	100	100	100	102
4	99	96	99	99	100	100	100	100
Tot.	396 / 400		399 / 400		401 / 400		402 / 400	

system was tested for flow rate by loading ball bearings (diameter ~ 4 mm) into a plastic straw and dropping them into the sensor tube. From a height of 25 cm above the bottom of the sensor tube, a single ball bearing takes approximately 225 ms to pass through the tube. Twenty-five ball bearings were dropped from the plastic straw at the same time and were counted at 100% accuracy. This is an approximate flow rate of 110 ball bearings/s and far exceeds the present demands of the handling system as well as providing adequate head-room for future developments.

Small-size testing was done with objects of known diameters. The instrument of choice for these tests was small drill bits, which provided useful data for the discrete LED systems. For the pixel array chip, carbon resistor legs with diameters ~0.8 mm are seen clearly in the analog sample output of the pixel array chip when viewed on an oscilloscope. The shadow cast by the resistor leg is approximately 5 to 7 analog samples wide. The system threshold voltage is very capable of being adjusted to a level to detect this shadow. Whether something this small is counted accurately is a function of the setting of the threshold voltage, the presence (or absence) of foreign object interference in the lens assembly, the steadiness of the assembly's mounting (specifically the LEDs), and the width of the digital filter in the CPLD.

5.5 Summary

This thesis presented the work involved in the design, simulation, construction, and testing of a system for counting small objects such as pharmaceutical pills. The limiting constraint for this design was to keep the cost of the counting system low enough that

small pharmacies could afford the machine. General methods of counting objects were researched and examined for use in this application. Most methods were eliminated because of costs; finally, LED-PT light beams were identified as the most cost-effective method. Commercial LED-PT sensor devices are available, but they are also too expensive for integrating into a small counting system.

The system uses a microcontroller to operate the motors of the pill handling system, keyboard, operator display, and overall counting functions. The microcontroller worked well with the exception of the sensing and counting tasks. Thus, it was decided by the primary system designer, Dr. Frank Speckhart, to design custom electronics for the sensors. His initial attempts improved the accuracy but used a large number of MSI 74xx logic chips. This author was contacted to replace the glue-logic with a CPLD. The first designs revealed that accuracy could be greatly improved by using a synchronous design instead of a timing critical asynchronous design. Pattern recognition masks were developed, tested, modified, and retested to detect the edge of the pills as they fell into the sensors. This method brought great improvements to accuracy for most size pills, but smaller pills posed two problems. First, the use of many LEDs that are constantly on caused blind zones in the sensor areas where pills could fall through undetected. This problem was eliminated by pulsing the LEDs and sampling the corresponding PT when its LED was in the ON state. This solved the problems of nonparallel light and improved accuracy so that no pills were missed that were larger than the sensor spacing.

The second problem was the sensor spacing. Small, thin pills can fall inbetween the sensor beams in such a manner as to cause two separate pulses at two separate times,

resulting in a double count. This problem was corrected with a new design that uses a pixel array chip with a density such that no pill can fall through undetected. This new design required the use of a single LED and a lens to create parallel light through the sensor region. This arrangement is currently giving counts of 99.867% accuracy at a flow rate of 5—15 pills/sec.

5.6 Future Work

The next step will be to redesign the board layouts for the four-board assembly. Better connectors are needed for assembly of the system as well as a slightly smaller tube for better coverage by the pixel array. Test points will need to be added for bench testing in an assembly environment as well as maintenance over the life of the product. Mounting hardware must be designed so that the system is optically stable during operation.

Once an optically stable prototype system is assembled, more experiments with the CPLD program can take place. Experiments with different filter widths in the digital filter and adjustment to the bandwidth of the RC filter at the pixel array chip should be performed to find optimum values. Larger digital filters in the CPLD can be implemented as counters instead of longer shift registers. This would allow longer strings of ONE's and ZERO's to be detected without consuming additional flip-flops in the CPLD.

If future sales of the counting machine are large in number, then serious consideration should be given to replacing the MACH-210 with one large custom gate-array. However, this may only be profitable if the sale of large quantities are greater than

the conversion costs and the present pattern recognition logic proves satisfactory. If future changes are anticipated, the CPLDs in inventory could be reprogrammed for the new design, where otherwise, a company could be stuck with a large supply of custom gate arrays that contain obsolete programming.

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VITA

James Wayne Walker II was born January 19, 1964, in Nashville, Tennessee, to James and Jonne Walker. When James was 11, his family moved to Wildersville, Tennessee. James attended high school in nearby Lexington and later attended college at Jackson State Community College in Jackson, Tennessee. James married Sandra Lee Eskew in 1984 and she gave birth to their first child, Heather Renee', later that year. James enlisted in the U. S. Air Force in 1986 and was trained in Ground Radio Electronics Maintenance. He and his family were stationed at San Vito Air Station, Italy, for his entire enlistment. James received the Air Force Good Conduct Medal and Air Force Achievement Medal. He was Honorably Discharged in December 1989. In January 1990, James enrolled in classes at The University of Tennessee and enlisted in the Tennessee Air National Guard. He was on stand by status during Operation Desert Shield and Operation Desert Storm and was Honorably Discharged in March 1992. He completed his B.S. degree in electrical and computer engineering in December 1992 from The University of Tennessee, Knoxville. James began work on an M.S. degree in electrical engineering in January 1993. During this time he held intern positions with CTI PET Systems of Knoxville and Oak Ridge National Laboratory. He was hired as a full-time staff employee by Oak Ridge National Laboratory in January 1994. James completed his M.S.E.E. degree in August 1995. He currently makes his home in Knoxville, Tennessee, with his wife Sandra and daughter Heather. James enjoys church activities, racquetball, coaching youth league basketball and softball, gardening, and playing the guitar.