# DESIGN OF A DE-SKEWING SYSTEM FOR AUTOMATIC BILL HANDLING MACHINES

by

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Submitted to the Department of Mechanical Engineering on June 4, 1990 in
partial fulfillment of the requirements for the degree of Bachelor of Science.

## Abstract

A method for de-skewing notes in automated bill handling machines has been designed. This method may be used to improve the reliability of bill handling. The largest cause of error in teller machines are notes that are not oriented properly. If a note is twisted or skewed, it has an increased likelihood of jamming in certain sections of the machine. Correction of the bill's misalignment should decrease the number of jams and increase the overall reliability of the machine.

The correction process involves rotation of the bill to straighten it. The rotation is achieved by pinching one end of the bill while it travels along the transportation belts of the machine. There are two narrow belts that transport a bill, one near either end of the bill. At the point of pinch, the bill stops moving. While it is pinched, the belt nearest the pinching device slides over the bill while the other belt continues to move the opposite end of the bill. The point of pinch, thus serves as a pivot point which the bill rotates about until the pinching device is released.

The pinching device used is a solenoid. The time the solenoid is powered is determined by the skew and speed of the bill. The skew of the bill is detected by two optical sensors. The signals of these sensors are sampled by a computer which controls the solenoids. A second set of sensors located after the straightening device determine the success of the skew correction.

Tests of the prototype correction device show it is capable of straightening bills. A maximum handling speed of four notes per second was achieved. Currently, bill handling machines run at seven notes per second. The reliability at this speed was poor. Improvements to the control system will yield faster and more reliable skew correction. Specifically, the solenoid activation timing must be improved. Revision of the timing system may require an additional data acquisition board.

| | |
|---|---|
| Thesis Supervisor: | Professor Harry West |
| Title: | Assistant Professor of Mechanical Engineering |

# Dedication

Special thanks to my parents, grandparents, sister, Kelly, GM and my friends who have helped to make MIT the best four years of my life.

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# Chapter 1

# Introduction

Omron Tateisi Electronics is a large, Japanese company with a diversity of technical strengths. Specifically, the company works with factory, laboratory, bank, office, retail and medical automation. The company had over two billion dollars in sales during the past year. The company employs nearly seven thousand people and holds about a quarter of the nation's business in automated teller machines (responsible for about ten percent of total sales). Omron has sponsored our design team to improve their automated bill handling machines.[1]

The project has two major goals, the first is to improve current bill handling machines. Desired improvements include increased speed and reliability. Generally, these two parameters are inversely related. The second part of the project's work is to brainstorm new concepts for teller machine designs. An improved design will be smaller, cheaper, faster and more reliable. This thesis is concerned with the first goal.

An automated bill handling machine that Omron produces is called the ABIO (Automatic Bill In/Out) machine. From now on, this device will be referred to as the ABIO. This machine counts and sorts Japanese currency (Yen) either being deposited or withdrawn. Deposited bills are fed directly into the machine as a stack (see Figure 1-1). The machine automatically feeds the bills one at a time past a recognition device. The recognizer uses optical methods to determine the values of the bills. After being counted,

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[1] Members of the project are Professor Harry West from the Mechanical Engineering Department of MIT; Ross Levinsky, a first year graduate student of the same Department; Mr. Ryuichi Onomoto; and Mr. Ichiro Kubo. Mr. Onomoto is a Mechanical Engineer from Omron, who joined the team during the fall term of 1989. Mr. Onomoto designed various components of the current bill handling machine and his expertise was invaluable to the project. Mr. Kubo is a visiting Electrical Engineer from Omron. Mr. Kubo contributed his computing and electronics knowledge critical to the success of the project.

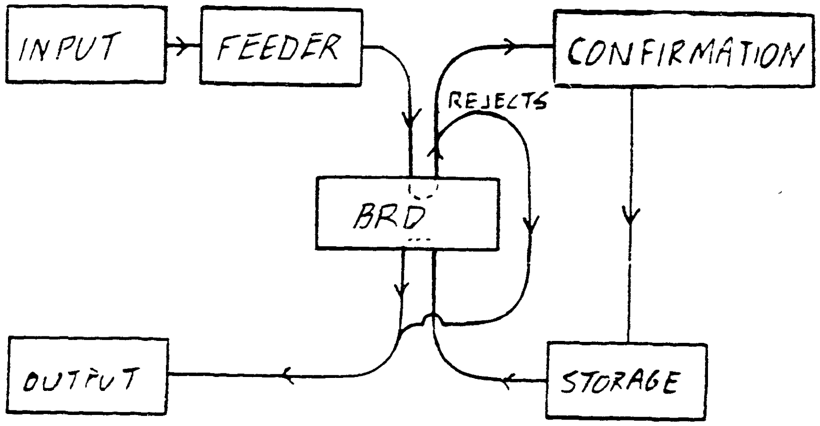


Figure 1-1: Schematic diagram of ABIO

the bills can then be deposited. When the bills are withdrawn, they are recounted and exit the machine one at a time to form a stack. To accomplish these functions, Omron's ABIO transports bills using a belt system. This complicated system occasionally will jam. A jam is more likely if there is a problem with a bill. Problems include torn bills, wrinkled bills, two bills stuck together and bills that are not oriented properly. The largest cause of jamming is a bill that is not oriented properly (a skewed bill). Finding a way to de-skew bills is the first part of the team's work.

The jamming problem can be relieved in two ways; either a jam will need to be corrected or prevented. Correcting a jam is difficult because it can happen in any part of the machine. Preventing a jam caused by a skewed bill is easier than correction because there are only a few places where a bill may be skewed. The most common place skewing occurs is during the feeding of the bill into the belt system. The feeding problem is another area of research and potential improvement for current ABIO machines. If the bill is straightened or de-skewed directly after the feeder, the bill is less likely to jam. Once the bill is properly oriented, its travel through the belt system is very reliable. This thesis work is the design of a de-skewing system to detect and correct skew immediately after the feeder. The solution to the problem will include the design and construction of a prototype mechanism for de-skewing.

As background, various de-skewing concepts, the characteristics of Yen and information concerning the current ABIO are presented. The prototype device, the control of the device and its testing comprise the main portion of the text. Finally, the prototype is evaluated for potential application to the ABIO.

# Chapter 2

# Motivations and Techniques for De-skew

Omron's ABIO is an exceptional machine. It operates very reliably despite its complicated tasks and many moving parts. Laboratory testing indicates the machine experiences one error for every seventeen thousand notes that it handles. In the field however, the error rate is much higher. Omron has set a goal of one error for every fifty-five thousand notes handled. We hope to approach this goal by straightening skewed notes.

Skewed notes cause many of the jams within the machine. As seen in Figure 2-1, jamming accounts for almost half of the errors mentioned above. Skewed notes are also directly responsible for almost forty percent of the Retry-Over errors (or eight percent of total errors). A Retry-Over error requires reprocessing of a rejected bill. It is clear that helping to correct the skewing problem will greatly improve the reliability of the ABIO.

The feeder is the main cause of skew. A skewed bill does not guarantee a problem, but the likelihood of a jam increases. The most frequent locations of jamming of a skewed bill are at the diverting mechanisms and the cartridge feeders. The cartridge feeder removes bills from the storage cartridge and introduces them to the belt system during withdrawal. A diverter is a mechanical switching device that is used to transfer bills from one belt system to another at a fork in the bill's path. The diverting mechanism assumes a certain spacing between bills and utilizes that space to move itself (switch) into proper position. If the diverter is switching as a bill passes, the bill may jam. In the event that the bill jams, it is likely the bills following it will also jam. A jammed bill is deformed by the moving belts in such a way that reversing the belt system is unlikely to free it.

Skew of bills limits the speed of the machine. It is desirable for the machine to operate quickly (a goal of twenty notes per second) and reliably. Generally, the faster the

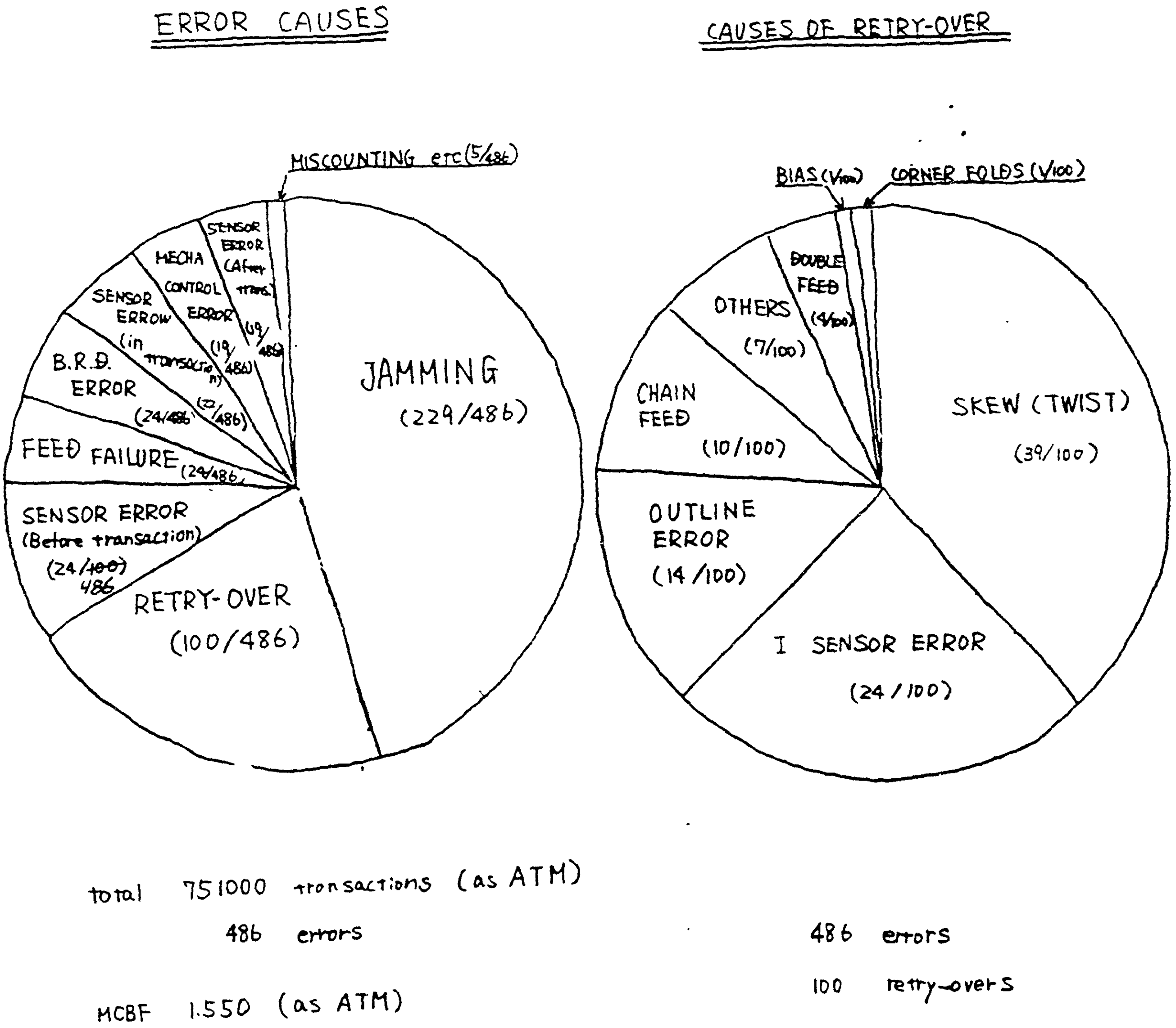


Figure 2-1: Breakdown of errors for the ABIO machine [Omron 90]

machine operates, the less reliable it is. The probability of skewing of a bill during feeding increases with the increase in speed. Thus, solving the skewing problem may allow the machine to operate faster.

As notes age, their probability of skewing in an ABIO increases. The reason for this is that aged notes are more likely to be wrinkled, torn, and folded. All of these characteristics make notes more difficult to handle. As noted in Appendix A, U.S. currency is in poorer condition than Japanese Yen. Because of this, handling used U.S. currency presents problems with the current ABIO machine. A de-skewing system will allow the machine to handle older notes which makes it useful for the U.S. market.

Once a machine is jammed irreversibly, a bank technician must remove the jammed bills. The operational time lost is of significant cost to the users and owners. The repair of the problem is also of substantial cost. This and the reasons mentioned above serve as motivation for a solution to the skewing/jamming problem.

Two obvious solutions to the problem are to stop the cause of skew or to correct skew. To stop the cause of skew, the feeder will need to be improved. This problem is being pursued as another project. My project is concerned with correcting the skew of a bill. In the following paragraphs, a description of various concepts for de-skewing bills are presented. The pinch method is the technique that we pursued and will be described more extensively in the following chapters.

## 2.1 Pinch

Bills are transported by a belt system described in Appendix B. Each bill is "sandwiched" between two upper and two lower belts as seen in Figure 2-2. The pinch method takes advantage of the separate belt systems. Analogous to the turning motion of a treaded vehicle (a tank), if the speed of the ends of the bill are not matched, it will rotate. By pinching one side of the bill, it will be slowed and the opposite side will rotate forward under the forces of the belt on that side. If at the point of pinch, the translational velocity is zero, the bill will rotate about the point of pinch.

It is necessary to have two pinching devices, one on either side of the bill. The

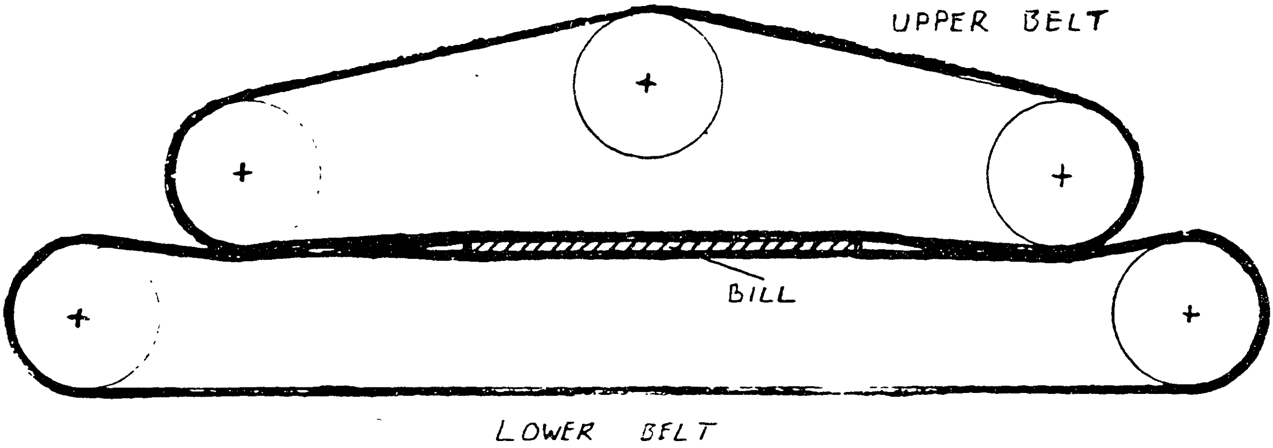


Figure 2-2: Transport of a bill within the belt system

direction of skew of the bill will designate which pincher will be used: the pincher encountered first by the bill will be used to allow the other end to "catch up". An increase in the time a bill is pinched will increase the rotation of the bill. At or above a critical pinch force, the bill will stop underneath the pincher and will rotate about that point as previously mentioned. It can be seen that the pinch method is a simple process. It would be the least expensive to implement in the ABIO if it proves successful.

The pinch method shifts bills back during skew correction. This shift decreases the necessary spacing between the bill and the one following it. If the skew of the bill initially was large, it is possible the straightened bill may overlap with the following bill (see Figure 2-3). The overlap may present other jamming problems. A solution to this problem using

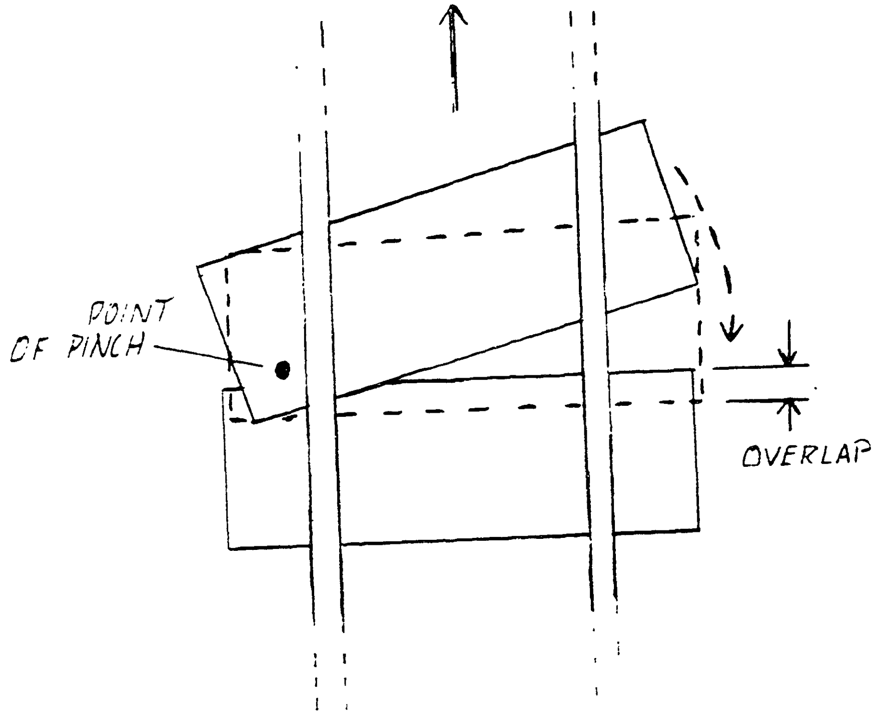


Figure 2-3: Demonstration of overlap between a straightened bill and the following bill

the pinch method is to move the following bill back too (pinch both ends so that it is slowed). This would leave about a half of the normal gap on either side of the following bill (the following bill will approach the bill following it). Another solution to the problem is to keep the skewed bill from shifting back.

## 2.2 Differential Rollers

The differential roller technique would not shift the bill. The bill would be straightened by a pair of driven rollers spinning in opposite directions. The rollers would be positioned at the ends of the bill as the pinchers were from the pinch technique. As the skewed bill passes under the rollers, their speed would be altered so that the "slow" (lagging) end of the bill would be accelerated forward and the "fast" (leading) end would be slowed. This turning motion is very similar to the pinch method, except that the center of rotation is at the center of the bill instead of at the point of pinch. Thus, the bill only rotates; there is no translation of the bill's center with respect to the belts.

The control of the rollers is a difficult problem. Achieving the correct roller speed at the right time is critical. If the rollers slide with respect to the bill, the modeling of the forces (and position) of the bill is complicated. There is also a geometry problem that may cause the bill to crumple as the rollers position it. By forcing one end of the bill against the direction of travel of the belts, the bill is likely to buckle or fold back on itself under the compressive loads of the belt on that side; see Appendix J. Although the rollers provide a solution to the shift problem, their complexities makes their use less attractive.

## 2.3 Differential Belts

Similar to the differential roller idea, skew could be corrected using a differential belt system. The differential belt system would have independently driven belts (one on either end of the bill). If a bill was skewed, one belt could be accelerated while the other was braked to adjust the bill's rotation. This technique solves the interface problem between the rollers and the bill (assuming the transition into the system from the normal belts is not a problem). While a bill is in the correction belt section, its speed may be altered. While entering and exiting the section though, the bill's speed must be matched to the speed of the machine. The correction section is limited to the width of one bill (so that only one bill can be in the section at any time). If there are multiple bills in the section, all the bills will be rotated the same amount. This is true even if one of the bills is not skewed. If the belts are short enough to hold only one bill there may be insufficient room to de-skew the bill.

## 2.4 Removal of a Jammed Bill

A different approach to the jamming problem is to find a solution to the effects of the problem instead of a solution to the problem itself. Various concepts for removing a jammed bill were formulated but none of the ideas appear feasible.

### 2.4.1 Robotic Removal

A manipulator at the side of the machine would reach into the machine to remove jammed bills. This robot would replace the technician (who also reaches into the machine to remove a bill) in the case of a jam. This technique would be very expensive.

### 2.4.2 Shredder

As mentioned earlier, jamming tends to occur at the diverters. If a paper shredder were a part of every diverter, jammed bills could be shredded and removed. The small strips of paper would fall out of the path of the other bills to be removed at a later date. Although shredding money is expensive, it may be cheaper than losing the time on the machine.

### 2.4.3 Incinerator

Similar to the shredder idea (mechanically expensive), jammed bills would be destroyed. In the event of a jam, an automated torch would incinerate any bills concerned and the ash would fall clear of the other bills. The reliability of this technique is questionable. A major concern is that each ABIO is capable of holding 20,000 dollars worth of Yen.

# Chapter 3

# Test Apparatus

This thesis describes the development of a pinch de-skewing device. The project's goal is to design, build and test a de-skewing device that may be implemented into the ABIO. This chapter describes the prototype design and apparatus for the de-skewing device.

## 3.1 BRD Test Apparatus

The construction of a test apparatus is a difficult endeavor. In addition to the test section where the notes will be manipulated, there must be a feeder that brings notes into that section and a bill collector afterwards. Fortunately, Omron provided us with a test apparatus used to test prototype Bill Recognition Devices (BRDs). This device (shown in Figure 3-1) consists of a feeder, a test section and a collector. Drawings for the test section of the BRD test apparatus are given in Appendix C. The feeder for the test device is incorporated in the storage container shown in Figure 3-1. The collector for the test device stacks the bills as they exit the machine. The collector reduces the bills' velocity to allow them to stack neatly. The test section is the only portion of the machine that needed to be constructed for the de-skewing device.

## 3.2 Belt System of Test Section

As mentioned earlier, if the de-skewing device works well, it will be installed within the ABIO. It is desirable for the de-skewing device to be easily installed. For easy installation, the bill's path needed to be similar to the paths found within the ABIO so that minimal modification will be necessary for it to be used. The same dual belt system

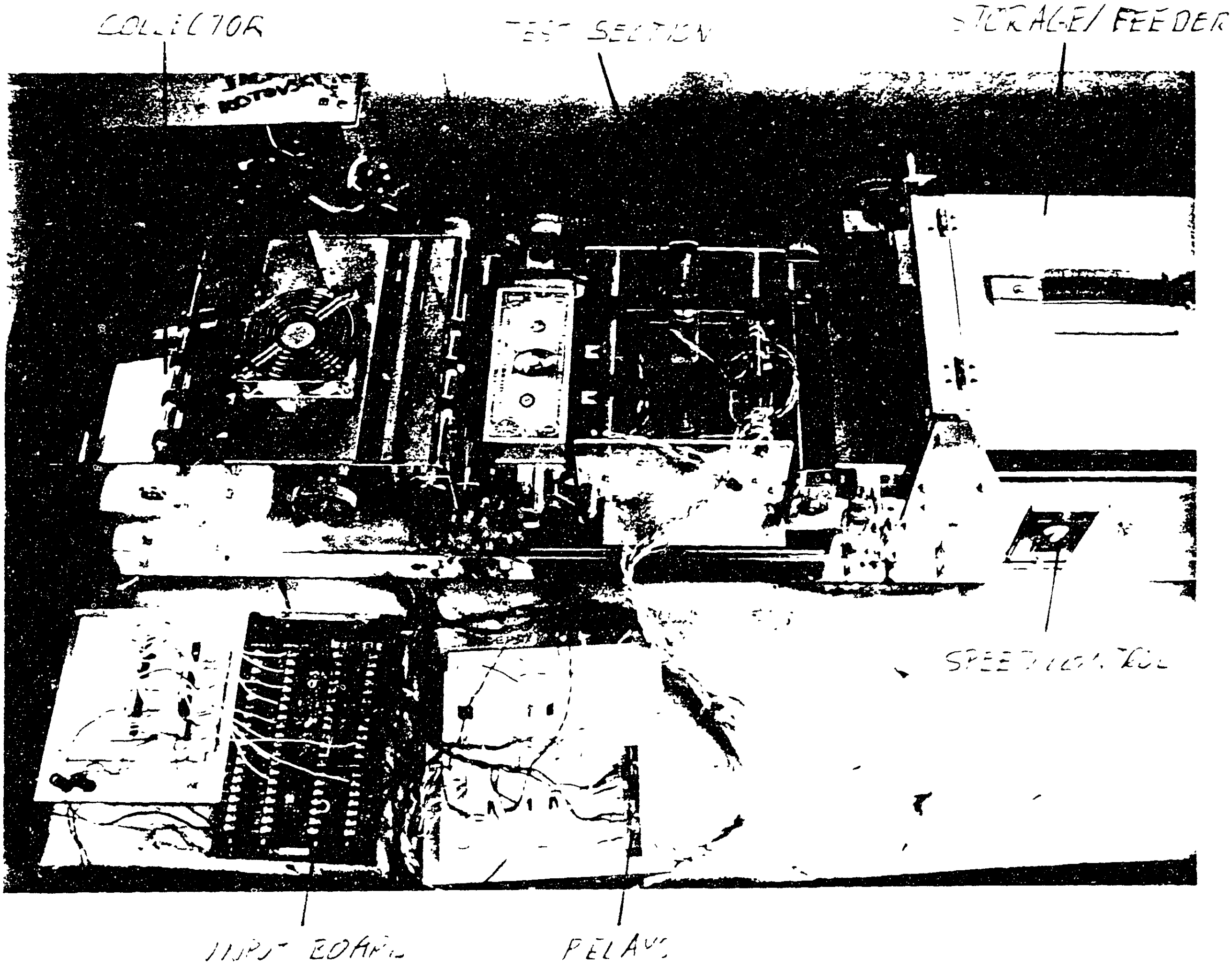


Figure 3-1: Omron's BRD Test Apparatus

described in Appendix B was used for the test section. The tension of the belts is also the same as found within the ABIO. The only variation between the ABIO's belt systems and the test apparatus' is the spacing of the pulleys (in general, the spacing within the ABIO is smaller).

The increased spacing of the pulleys found in the test section decreases the pinching force on the bill. The pinching force is the amount of squeeze the bill experiences between the belts. The smaller the pinching force, the easier it is to move the bill relative to the belts. Thus, within the test section it is easier to de-skew bills than in the real ABIO. A higher pinch force test will be necessary to prove the effectiveness of the de-skewing device before it can be applied to the ABIO. Otherwise, the ABIO will need to be altered to include a lower pinch force de-skewing area. The effects of pinch force on de-skewing will be discussed in the following chapter.

A parts list and drawings of the test section can be found in Appendix D. The belt system was designed to leave ample room for any hardware that needed to be installed or moved within the test area to keep the machine flexible. The test section was built on the BRD test plate that can be easily removed from the rest of the machine by removing two screws. Pulleys may be moved or added within the test section by simply drilling the side plates. Future tests may require a modified pulley configuration to test under different pinch force conditions as previously mentioned.

### 3.3 Solenoids

The pinching actuators that will be used for the correction device are solenoids. The solenoids are mounted vertically such that when activated, the solenoid's core contacts the surface of the note. The solenoids are placed above the note as shown in figure 3-2. A return spring is used to keep the core from interfering with the notes while the solenoid is not in use. Underneath the note an aluminum "table" has been placed to provide a surface for the solenoid to pinch against. The clearance between the solenoid and the table (while not in use) is 3mm. The table has sloped edges (see Figure 3-3) to guide bent notes over it. If the leading edge of a bent note contacts the side of the table the note may jam. The tables and the solenoids are easily adjusted to allow variations in the placement of the pinch of the bill. Technical information concerning the solenoids may be found in Appendix E.

The solenoids are powered by a twenty-four volt supply. The switching for each solenoid is handled by a solid state relay controlled by the computer. Details concerning these relays also may be found in Appendix E.

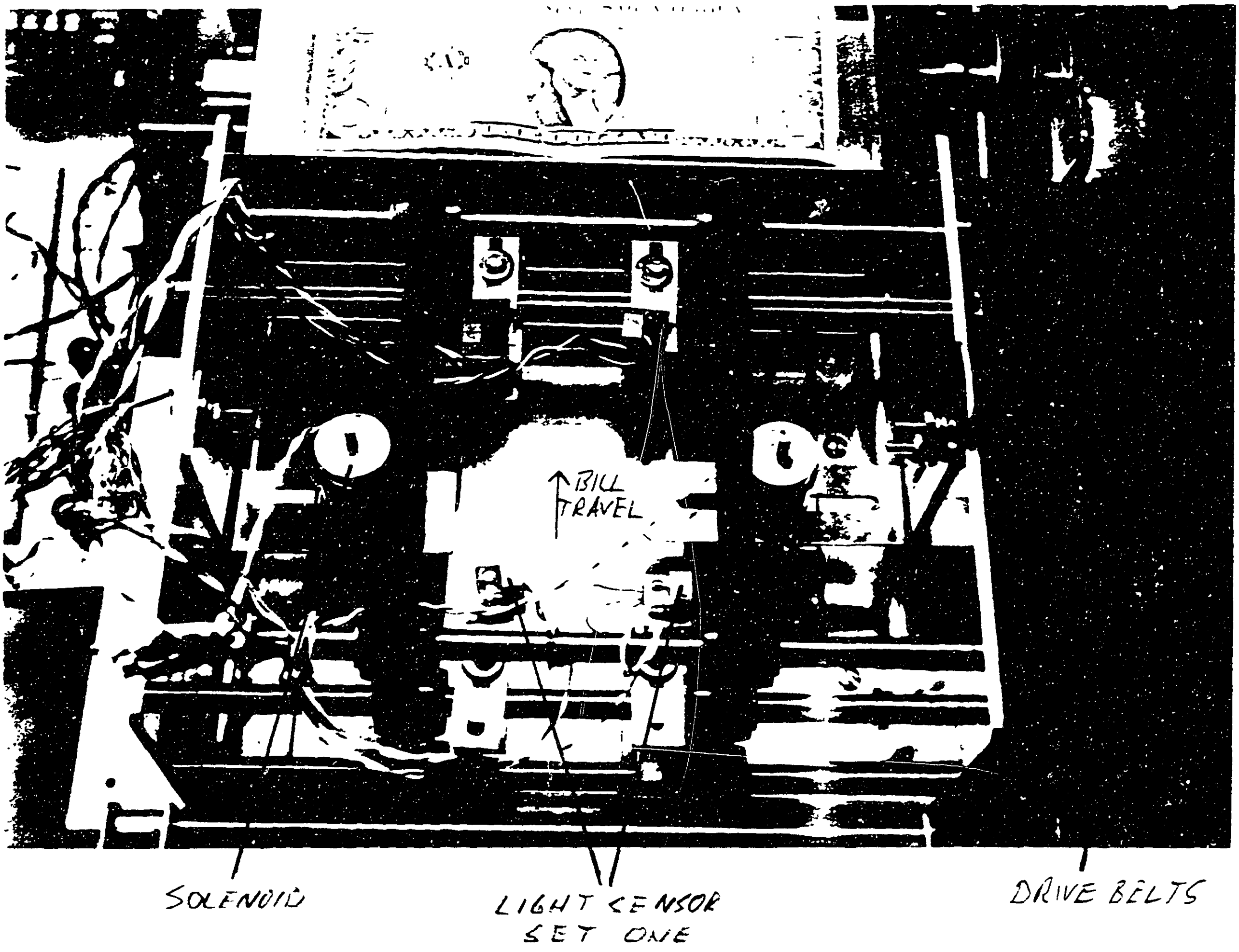


Figure 3-2: Bird's eye view of test section with solenoids

### 3.4 Optical Sensors

To determine the skew of a bill, optical sensors are used. There are four pairs of sensors, two pairs form a set. The first set determines the skew of a note before it enters the de-skewing area. The control system of the de-skewer determines the time of activation for the solenoids based on the amount the note is skewed. The amount of time necessary to

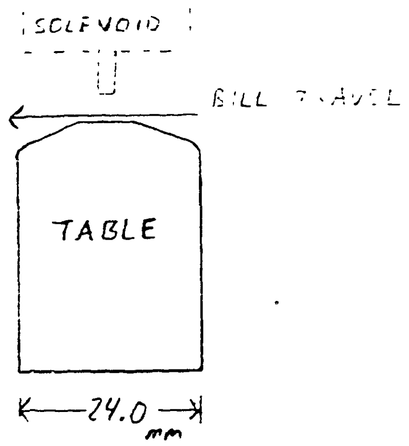


Figure 3-3: Side view of table showing the sloped edge aimed at preventing a jam

straighten a bill will be discussed in Chapter 6. The second set provides skew information after the de-skewer. The data from the second set is used as feedback to improve de-skewing for future bills.

A pair of sensors includes an infrared LED and a phototransistor. The sensor pair is mounted so that a bill traveling through the test section will interrupt the infrared beam. Upon interruption, the phototransistor's emitter current falls to zero. The output of the phototransistor's circuit is a voltage drop across a resistor connecting the emitter to ground. Thus, as a bill passes between the sensors, the output of the sensor circuit falls from about five to zero volts. The circuit diagrams for the optical sensors and their specifications can be found in Appendix F.

The sensors are mounted as shown in Figure 3-4. A bill that is perfectly straight will interrupt the signals of both sensors in a set at the same time. If the bill is skewed, the leading edge of the bill will interrupt the sensors in a set at different times. The computer evaluates the time difference between the sensors to determine the skew of the bill. The calculation of the skew of the bill using the difference in times from the optical sensors and measurement of the speed of the bill will be shown in Chapter 6.

Figure 3-4: Top view of test section showing placement of optical sensors.

### 3.5 Speed Sensor

It is necessary to know the speed the notes travel to properly straighten them. Two options were considered for this task. The first was an optical encoder mounted on one of the drive shafts. This technique requires minimal mechanical power to operate and is very accurate. This method was not used due to difficulties with the input timing of the computer. The second option was a tachometer. This option was selected for its simplicity of operation. The output of the tachometer is a single analog signal. This signal can be connected to the input board of the computer and directly sampled. The tachometer has less accuracy and requires greater mechanical power to operate than the encoder. These disadvantages do not present a problem with the accuracy necessary and the power available in the de-skewing device. Specifications for the tachometer used are given in Appendix G.

# Chapter 4

# Functional Requirements of Prototype design

To build the prototype correction system, various components were purchased. For each of these components, more than one option was available. The requirements and reasons for selection of each of the components will be presented in this chapter.

## 4.1 Pinch Device

An actuator is needed for the pinch device. The requirements for the actuator are presented in Table 4-I.

Table 4-I: Pinch Actuator Requirements

| | |
|---|---|
| -Size | Ideally 0.5"x1.0"x1.0" |
| -Cost | $30 is a goal for the cost of the total system. A limit for each actuator (to approach goal) is thus $15. |
| -Reliability | The device needs to be capable of performing the same operation over a million times if it is implemented in the ABIO. During this life cycle, it must behave in a predictable manner. |
| -Force | 1 pound is an experimental estimate of the force required to stop a bill within the ABIO belt system. This force varies with the location in the machine. |
| -Speed | The actuator should react in 2.7 milli-seconds. |
| [2] -Range | A stroke of 3mm. |
| -Power Supply | The actuator should not demand an unusually high voltage. It is desirable to power the actuator with the supplies available within the ABIO (5V and 24V). |

---

[2] Calculation of the time of activation: {.09 rad rotational accuracy of the bill (5 deg.)}x(90mm radius of rotation of the bill)/(3040 mm/s maximum bill speed) = 2.7 ms

Three types of actuators were considered for the correction device; piezoelectric actuators, pneumatic actuators and solenoids. The piezoelectric actuators were initially considered because they can operate at very high speeds. The piezoelectric actuators could not be used due to insufficient force. For the range of motion necessary, these actuators provide less than an ounce of force.

There are a number of pneumatic actuators that meet the force and size requirements of the correction device. The reason these actuators were not chosen was the cost and size of the pump to power them. An electrical system would be much more cost and space effective.

A solenoid was chosen for the prototype because this actuator comes closest to meeting all of the requirements listed. The solenoid selected meets the force, stroke, reliability, and power criterion for the pinch device. The cost is very close to the desired value (in bulk). The solenoid is larger than the desired size, but this is a flexible requirement. The time of response of the solenoid used also is larger than desired. As seen in Appendix E, for 3mm of travel, the solenoid response time is 6ms. Although this solenoid is slower than desired, it is more powerful than necessary (see Chapter 8). For solenoids, speed is sacrificed for force. Thus, a smaller solenoid (which still meets the force requirement) may be chosen that will operate faster. From the same company, a solenoid with sufficient force and a speed of 2.7ms is available, but the stroke is only 1.5mm. The effects of a smaller gap size is discussed in Chapter 8.

## 4.2 Relays

Relays are necessary to control the solenoids. Desirable qualities for the relays are as follows:

**-cost < $5**
**-activation time < 0.5ms**
**-input current < 10mA**

| | |
|---|---|
| -input voltage | < 5V |

The relays will be driven by the data acquisition board in the computer. The board is capable of putting out five volts at a very small current (about 10mA). For convenience, it would be useful to have a relay that is able to respond to this signal directly so that an amplifier will not be necessary. In addition, to protect the acquisition board when the relay is turned off, a low inductance is desirable. The only relay that meets all of these requirements is a solid state device. The Potter and Brumfield relay selected closely matched the needs of the prototype as displayed in Appendix E.

### 4.3 Skew Detectors

A sensor system is necessary to determine the skew of bills in the ABIO. The following qualities are desirable for the sensors:

| | |
|---|---|
| -dimensions | 0.5"x0.5"x0.5" |
| -cost | < $2 |
| -accuracy | within 0.2 ms |
| -unobtrusive | sense without contacting notes |

An optical sensor is most appropriate for this application. Many optical sensors meet all of the requirements listed above. Two sensors were considered, a reflective and an interrupt sensor. Each sensor system contains a source (LED) and a detector (phototransistor). In the reflective assembly, one unit houses both components. The detector senses the reflected source. This device is very convenient to mount within the machine but the Yen does not sufficiently reflect the source. The interrupt system has the same source and detector, but the components are separate (see Figure 3-4). An infrared system was chosen to allow the correction device to be operated under normal lighting conditions.

## 4.4 Power Supply

The correction system is powered by two supplies. A five volt supply powers the sensor system. Most of the optical sensors considered for the project require five volts. This supply was chosen because it is very common. The other supply is twenty-four volts which powers the solenoids. The solenoids may be powered under a range of voltages as noted in Appendix E. A twenty four volt supply was chosen because it also is very common. The ABIO includes both a twenty-four and a five volt supply.

## 4.5 Table

The table under the solenoid was formed from an aluminum block. Aluminum was used because it provides the stiffness the components of the machine require and it is easy to work with. Originally, the surface in contact with the bill during skew correction was to be covered with a high friction material like rubber. The end of the solenoid's core (which also contacts the bill during correction) was also to be covered with a high friction material. After the solenoids and tables were installed, preliminary tests were conducted to evaluate their positioning. Not only did these tests show that the solenoid/table placement was effective, they also revealed the device would work without the higher friction material (for the belt pinch of the prototype). The tests also showed that a guide plate to lead the bills under the solenoid core was not necessary for the prototype. The use of a guide plate will be discussed in Chapter 8. Future experimentation will test the effects of a higher friction surface, guide plates and a reduced gap between the solenoid and the table.

## 4.6 Speed Sensor

A means to measure the speed of the bill was also necessary for the prototype. Two devices were considered; an optical encoder and a tachometer. The requirements for the speed sensor are as follows:

| | |
|---|---|
| -cost | < $50 |
| -accuracy | within 5% of actual speed |
| -output signal | able to easily interface with computer |

The optical encoder is more accurate than the tachometer but its output signal is more difficult to process. Although added accuracy is desirable, the tachometer is sufficient for the prototype's use. The encoder provides a square wave output that must be timed by the input board. The complications involved with the timing of the encoder's signal make this device much less convenient to use than the tachometer. The tachometer's output is simply scaled by a constant to provide the velocity; see Appendix G. For the convenience of use, the tachometer was selected to detect the speed of the machine. The tachometer is also less expensive. The speed sensor is needed only for the prototype device because the ABIO has its own encoder.

## 4.7 Data Acquisition Board

The data acquisition board should have the following features:

| | |
|---|---|
| -triggering | software controlled within 1ms |
| -clock | accurate to 1ms |
| -input rate | 2kHz (sampling/conversion rate) |
| -output rate | 2kHz |

# Chapter 5

## De-skew Forces

The notes within the de-skewing apparatus will be straightened by slowing (stopping) one end of the bill with a solenoid. A detailed description of what happens to the note during this straightening period has not yet been given. This chapter will analyze the mechanics of the de-skewing process.

A skewed note is shown in Figure 5-1. It can be seen that this note has already passed the first set of light sensors. Light sensor one (L1) was tripped first so solenoid one would be activated. The calculation of the time that the solenoid is powered will be explained in Chapter 6.

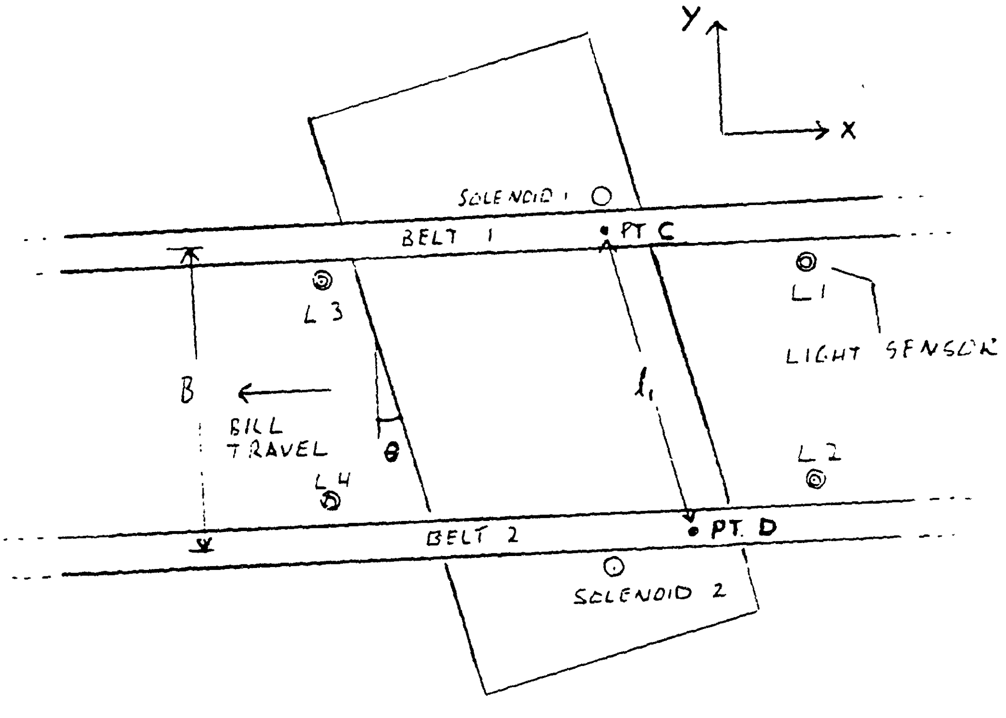


Figure 5-1: Dimensions of a skewed note

The solenoids provide a pinch force that is sufficient to stop the portion of the bill underneath it. For this case, the note will rotate about the point of contact with the solenoid as mentioned in Chapter 2. The core of the solenoid is capable of rotating with the bill, but there is a drag force between the core and the body of the solenoid. Because of this resistance to core rotation, the area of contact between the solenoid and the bill should be minimized to help prevent the bill from buckling. This is accomplished in the prototype device by direct contact of the core's end with the bill (as shown if Figure 3-3). With this configuration, a buckling problem at the interface of the solenoid and the bill was not encountered in the testing of the device.

High belt pinch forces do not lend to smooth sliding between the bill and the belt. A potential problem area due to high pinch forces is between pulleys of the belt system. Thus, it is desirable for the de-skewing device to be located at a belt section with a span between pulleys greater than the width of the bill. At the other extreme, very low belt pinch forces also present a problem. If the belts do not pull with sufficient force, it is possible for the bill to stall or stop. Thus, the belt pinch force must be within a certain range for the de-skewing device and belt system to work properly.

Note buckling presents another problem with the drag force of belt one. If the solenoid pinches the bill near the leading edge of the bill, it is possible that the bill will buckle as the back of the bill is "pushed" or compressed against the solenoid by belt one. This problem is easily solved by pinching the bill at its trailing edge. With this solenoid placement, the bill section under belt one is under tension (along the critical dimension) and does not tend to buckle (see Appendix J). The tendency for the bill to buckle decreases with accurate solenoid placement and low belt pinch forces.

It can be seen that belt pinch effects the de-skewing process because of the sliding motion between belt one and the bill. Belt pinch also effects the bill at its interface with belt two. As the note is rotated, there is motion between it and belt two. First, there is the slight rotational motion between the bill and the belt. The effects of the forces due to the rotation are relatively small compared to the sliding at belt one. A larger problem at belt two is the translation that occurs there.

By studying Figure 5-1 the reader will see that the length $l_1$ is greater than the length B. The more the note is skewed, the greater the difference between $l_1$ and B. As the note is straightened, the point C on the bill does not move significantly in the Y direction. This is due to the short distance between point C and solenoid one (the bill's center of rotation with respect to ground). Point D on the other hand, translates in the Y direction enough to present a potential problem. The shift in the Y direction of point D is the difference in lengths of $l_1$ and B. If the belt pinch is too great, the bill's stiffness in the Y direction may not be sufficient to keep the bill from buckling in that direction. The result of this is a "bow" in the bill between the belts. This bow may present a jamming problem later in the machine. The bowing problem intensifies with increased skew and increased belt pinch.

There are methods that may help to prevent the bowing of a bill. As previously stated, the bowing of a bill results from a lack of stiffness in the bill. This stiffness may be increased in a couple different ways. The first idea is a set of guide plates that would "sandwich" the bill. The spacing between the plates and the bill would need to be small so that the plates may keep the bill from bowing. Another technique is to bend or curve the bill to provide increased stiffness. If a bill is bent around the side of a cylinder, the bill will be stiffer (measured as a resistance to buckling) along the axis of the cylinder. If de-skewing was to occur as the bill traveled around the surface of a cylindrical drum, the bowing problem would be much less likely to occur. The drum would serve as a large pulley that the belts would pass over as any other pulley. The bill would only be in contact with the two belts. The non-bill side of the lower belts would be in contact with the cylinder. The solenoid would pinch the portion of the bill that extended beyond the edge of the rotating cylinder. Both of these ideas will help to relieve the bowing problem.

There are many forces and variables that affect the note during the rotations and translations of de-skew. As an extension to his feeder analysis, Ross Levinsky will provide a model of the note during de-skew. This model will provide a guideline for choosing parameters that will allow successful de-skewing. For the purposes of my thesis, a relatively low belt pinch was used to demonstrate the potential success of the de-skewing device. With this belt pinch and a sufficient solenoid force to stop the note underneath it, the correction of the note's skew is purely a geometric problem. Simply stated: the note rotates about the point of contact with the powered solenoid under the force of the opposite belt.

# Chapter 6

# Skew Correction Control System

The skew correction device is controlled by an NEC IBM compatible computer. This machine has a 386 SX processor with six expansion slots. The machine has been equipped with a Data Translation data acquisition board (details in Appendix H). This board is used to sample input data, run A/D conversions of the data and to provide output signals.

A hardware trigger is used to signal the computer that a bill is passing (see Appendix I). The trigger is the output of an AND gate. The two inputs to the AND gate are the outputs ($V_0$) of the phototransistor circuits of the first set of light sensors (see Appendix F). When no bill is present, each of the phototransistors is in the forward active region; there is an emitter current. The voltage drop across the resistor in the phototransistor circuit (roughly 4.8V) gives a "high" output. With both sensor's outputs high, the AND gate's output is high and the trigger is inactive. If a bill interrupts the LED's beam, the phototransistor is in cutoff and the emitter current is near zero (30 - 60 $\mu$A). With a low emitter current, $V_0$ (output voltage) is "low" (about 0.3 - 0.6 V). If one sensor's output voltage is low, the AND gate output is low and the trigger falls. A falling trigger prompts the board to begin sampling channel 0 (light sensor one) and channel 1 (light sensor two).

The board samples at 2 kHz; 1kHz/channel because the board alternately samples the two channels. Every sample undergoes an analog to digital conversion. The computer checks the first two samples to determine which sensor is low (or covered). A low analog signal (below a set threshold of 2.5 V), is converted to a zero digital signal. A high analog signal (above the threshold) is converted to a digital signal of approximately 4096 (12-bit resolution processor, see Appendix H). The covered sensor gives the direction of skew.

The computer continues to check the returned conversions from the board and keeps track of the number of conversions. At some point, the second sensor is covered and goes low. The computer checks at which conversion number the second sensor is covered. From the total number of conversions (running at 2kHz), the computer calculates the time differential between the covering of the sensors.

The time differential of the sensors can be used as the time of activation for the solenoids (see Figure 5-1). The wait time until the proper solenoid (the solenoid on the side of the light sensor covered first) is activated is determinated by the velocity of the bill. The velocity of the bill is calculated at the beginning of the control program by sampling the analog tachometer signal. This voltage input is multiplied by the conversion factor to give the bill speed (see Appendix G). This velocity is divided into a constant to give the proper delay of the solenoid activation. The constant is related to the spacing between the first set of light sensors and the solenoid. Dividing this distance by the velocity of the bill gives the time of travel to the solenoid from the first sensor. The constant is adjusted experimentally to get the solenoids to strike the bill at the desired location. This adjustment accounts for any delays in the computer, board, relays and solenoids.

The A/D conversions of the board continue to run at 2kHz even after both sensors are covered. The conversion number is used to clock the time delay of the solenoid activation. Once the solenoids are activated, an external clock measures the time of activation. During activation, the board sends a five volt signal to the relay corresponding to the correct solenoid. As long as the relay has a positive five volt input, the solenoid is powered through the relay (see Appendix E). Once the throw time is completed (same as the time differential of the light sensors), the solenoids are released, the conversion counter resets and the computer once again awaits the trigger.

This is one completed cycle of skew correction. Every bill that passes the first set of light sensors triggers the computer to begin the A/D conversions. The time differential of the light sensors must be above a certain threshold value to cause the solenoids to activate.

The threshold is determined by the maximum acceptable skew of a bill. For the ABIO the maximum skew acceptable is about five degrees. Thus, only bills above this skew will cause the solenoids to activate. The code for the initial control program is included in Appendix J.

Currently, the feedback control system is not in use. Initial testing required only the first sensors to be used. In future tests, the skew of the bill as it exits will be subtracted from its initial skew. The difference of these skews (light sensor time differentials) is the error in the skew correction. If a series of bills give errors, the errors will be averaged and incorporated as an offset in the solenoid activation time calculation.

# Chapter 7

# Skew Correction Tests

The skew correction device just reached its testing phase as this paper was being written. Initially, the machine was to be completed and operational about two weeks earlier. The delay in the completion of the project was the result of unexpected delays in the construction of the device, delays in the purchase of the computer and problems with the control system. Although I am fortunate that the project reached a phase where it could undergo initial evaluation, limited testing time prevented full testing of the device.

## 7.1 Skew Variation Tests

Within the ABIO, notes may be skewed different amounts. Thus, initial tests should evaluate the device's ability to correct various degrees of skew. Determining the success of skew correction can be accomplished in one of two ways. The less accurate method is to watch the bills at the collector to visually determine if they are straight. As previously mentioned, the collector greatly slows the bills down so that they are easily visible even if the test section is operating at ten notes per second. A more accurate technique for determining the device's success is to check the signal of the feedback sensors. The feedback sensors provide information to the computer so that it may adjust the solenoid firing times to improve the de-skew of future bills. The signal may be used directly to determine the skew after correction. The feedback signal also may be subtracted from the initial sensor signal to obtain an error signal. The error signal can serve as a measure of the device's ability to handle different skews. The results of these tests showed increased skew is more difficult to correct. The bowing of the bill and the control of the solenoids both present problems. Bow can be corrected with a guide plate. Improving the control of the device may require the purchase of an additional data acquisition board.

## 7.2 Speed Tests

The skew correction system can only be considered a true success if it is able to operate at the speed a real ABIO operates. Currently, Omron's ABIO transports notes at a rate of seven per second. For future machines, Omron hopes to achieve a goal of twenty notes per second. Skew correction at ten notes per second or faster would be a definite success.

To test the machine under different speeds, a range of skews should be tried. For each skew, the machine's speed should be increased until the correction is no longer dependable. Under preliminary testing, a speed of four notes per second was achieved. The reliability at this speed was poor due to problems with the control system. About ten percent of the bills were properly straightened. The cause of the problem was a fluctuation in the delay time until solenoid activation. At times, multiple bills would be straightened perfectly. Without warning, the solenoids would then cause a series of jams. This unpredictable behavior is the result of a clocking problem to be discussed in Chapter 8.1.7.

## 7.3 Continued Testing

As the project continues, various additional tests may be conducted.

### 7.3.1 Folded and Torn Bills

Skew correction of folded and torn bills determines the device's ability to accommodate to variations among bills.

### 7.3.2 Spacing Correction

To prevent overlap of bills, both solenoids may be activated to shift a bill straight back (see Figure 2-3 in Chapter 2). The amount of shift depends upon the amount of overlap between bills and the spacing between the bill to be shifted and the bill following it.

### 7.3.3 Variations in Solenoid Placement

The placement of the solenoids may effect the skew correction of bills. Testing may reveal improved skew correction for solenoid placement further from the belt. This variation and additional skew correction tests are discussed in Chapter 8.

# Chapter 8

# Discussion

## 8.1 Areas of Improvement for the Skew Correction System

This chapter will describe improvements that will increase skew correction performance.

### 8.1.1 Smaller Solenoids

For the test apparatus, the solenoids chosen were larger than necessary for the belt system used. The reason that these particular solenoids were selected was to insure sufficient force was available for testing skew correction. Using larger than necessary solenoids provided flexibility for testing under different belt pinch forces (a variation we did not formally test). As described, an increased belt pinch force requires a greater solenoid force to stop the bill. If a belt tension similar to that used in the test apparatus is used, smaller solenoids may be used.

A smaller solenoid has certain advantages. The reaction time of a solenoid generally decreases with a decrease in the mass of the core (the moving portion of the solenoid). A smaller reaction time is desirable because it allows skew correction at higher note speeds and increased accuracy in placing the solenoid on the note. In the testing of our prototype, the speed of the solenoid never limited the speed of operation. As skew correction continues to improve though, the speed of the solenoid may not be sufficient for accurate skew correction.

A smaller solenoid is also desirable for the final skew correction device that may be implemented in the ABIO. Space is limited within the machine. A small change in the size of the correction device may greatly influence the cost to install it within the machine.

### 8.1.2 Solenoid Placement

The solenoid's placement may be varied along two dimensions of the bill. By adjusting the solenoid firing time, the point of contact between the solenoid and the bill may be changed (along the direction of the bill's travel). It is desirable for the solenoid to hit the trailing edge of the bill to prevent buckling as discussed in Chapter 5. The position of the solenoid along the length of the bill also may affect the bill's behavior.

This variation can be tested by repositioning the solenoid and the table below it (both are fastened in slotted brackets). In the prototype device, the solenoids are placed within half of an inch of the belts (as close to the belts as the current device permits). If the solenoids are repositioned, they would be moved further from the belts and would contact the bill closer to its end.

This test was never conducted due to the size of the gap between the solenoid and the table. The gap allows sufficient room for a normal bill to pass (see Figure 3.3) but may cause a problem for folded or mangled bills. Bills that are badly bent may contact the solenoid or table and cause a jam. Guides leading the bill between the table and the solenoid would be effective in helping with this problem, but do not completely solve it. Therefore, it is desirable to place the solenoid where it is least likely to interfere with the varied notes.

The most predictable location of a bill along its length is at the belt. The belt helps to flatten folds or tears in the note. The further the distance from the belt (along the cantilevered bill), the greater the variation in the bill's position. This is one reason the solenoids were placed near the belts. Another reason for this solenoid placement is a possible shift in the bill's position. It is possible that the bill may be shifted (due to skew or other reasons) such that the solenoid may never have the opportunity to contact it. If placement of the solenoid farther from the belt is necessary, measures may be taken to reduce the likelihood of a jam. By providing guides or increasing the solenoid stroke (increasing stroke increases the solenoid/table gap), the jamming problem can be relieved.

The decision to mount the solenoids on the outside of the belts as opposed to the inside was based on the possibility of bill buckling. If the solenoids were mounted on the inside of the belt (which has the advantage of reducing the likelihood of bow), the bill may buckle when a solenoid fires. The portion of the bill under the belt nearest the driven solenoid would be forced to travel in the opposite direction of the travel of the belt. This analysis assumes the bill rotates about the point of contact with the solenoid and the bill does not translate underneath the solenoid. The bill is in compression when it is forced to travel against the direction of travel of the belt. A compressed bill is likely to buckle or fold due to the lack of stiffness in the direction of the belt forces, see Appendix I. Although there may be advantages to mounting the solenoids on the inside of the belts, the possibility of bill buckling dissuaded us from doing so.

It can be seen that varying the solenoid placement has many effects. It may be worthwhile in future tests to experiment with solenoid positioning to determine their ideal location. There is no certainty that an alternate solenoid position will improve skew correction, but it is a possibility.

### 8.1.3 Improved Feedback Control

The feedback system of the first prototype was designed to measure the skew correction success of the device. The error in the straightening of the bill may be used to adjust the solenoid's firing time for following bills. This is a useful feedback system if there are variations in the machine over longer lengths of time or if groups of bills are similar (eg. a variation in humidity). This technique does allow a number of bills to pass that may still be skewed.

A control system that would provide feedback as a bill is being straightened would be ideal. This device would accommodate variations between bills (eg. a very old torn bill followed by a new bill). Such a device would require a sensor system capable of determining the skew of the bill while it was in the test section. If series of light sensors located beside the solenoids were used, the position of the bill could be updated as the bill progressed through the device. This information could be used in one of two ways.

The correction device could operate without measuring the velocity of the bill. If a large number of sensors were used, the solenoid could be operated under bill position control. At any given time, the bill's position would be known with an accuracy directly proportional to the spacing between sensors. When the sensors determined that the bill was acceptably straight, the solenoid would release the bill. The maximum error in the skew of a bill leaving the device would be equal to the spacing of the light sensors.

This error can be improved by using the updated position feedback in combination with the velocity of the bill. This would be the same system used with a single set of sensors, but with increased accuracy. The single set of sensors (used in the prototype device) assumes the bill rotates about the solenoid and does not translate with respect to the opposite belt. These are good assumptions but they may introduce error into the system. As an example, the rotation of the bill about the solenoid assumes the bill is able to withstand infinite acceleration. When the solenoid is fired, there is a brief time required to stop the bill underneath it. Likewise, upon release of the solenoid, there is a brief time to accelerate the bill back to the speed of the belt. Using updated position feedback reduces the effects of these errors.

### 8.1.4 Rotating Solenoid Tip

The surface area of contact between the bill and the solenoid is very small for the prototype. If a guide plate or friction plate is attached to the solenoid the surface area may become substantially larger. An increase in the surface area increases the likelihood of bill buckling during skew correction. To help prevent buckling, the attachment should rotate freely about the solenoid's axis. As previously mentioned, the core is able to rotate about the same axis, but is influenced by drag forces due to contact with the solenoid housing.

### 8.1.5 Note Puncture

There are alternatives to pinching the note to correct skew. One of these alternatives is to puncture the note to create a more definite center of rotation. As discussed, pinching the note presents problems of buckling near the solenoid due to the rotation of the bill. If a fine needle were to spear the bill, this particular problem would be relieved. A puncture system could also be smaller because less force is required to stop the bill. Bill damage is the only problem with this technique. Every bill that is corrected will have a hole in it. The size of the hole can be minimized with small belt pinch forces. The smaller the belt pinch, the smaller the force required to decelerate the bill. For very small belt pinch forces, the hole may not be visible.

### 8.1.6 Wide Belts

Using a wide belt offers a solution to the bowing problem mentioned in Chapter 5. If a wide belt were included between the two standard belts, the bill would not bow (even under correction of large skews). The correction belt or wide belt would be positioned as shown in Figure 8-1. The pinch of this belt should be minimal because its purpose is simply to provide a guide for the passing bill. Basically, the wide belt serves as a moving guide plate to keep the bill in proper position. Not only does this belt keep the bill from bowing, it also flattens the bill out so that its position is known reliably. As discussed earlier, it is favorable for the bill's position to be steady. This improves the solenoid's performance by reducing unwanted contact between the bill and the solenoid and reducing the distance the solenoid's core must travel (see Appendix E for distance/time response behavior of the solenoid).

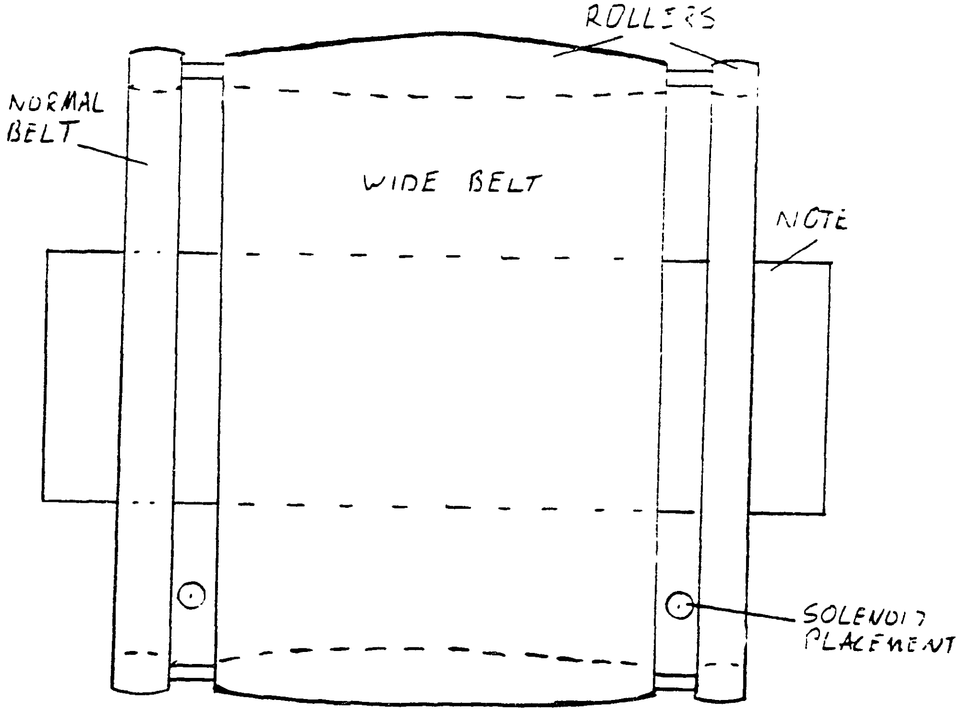


Figure 8-1: Configuration of wide belt system

### 8.1.7 Belt Stop

The prototype device stops a portion of the bill to accomplish skew correction. As discussed in Chapter 5, the motion between the belts and the stopped bill present various problems. A solution to the problem is to avoid the problem. If the belt is stopped with the bill, the buckling of the bill due to the belt's motion will not occur. This method of skew correction is discussed in Chapter 1.

# Chapter 9

# Conclusions

The skew correction system has achieved limited success. The device has been built and has proven to work. It has straightened bills skewed at various angles and traveling at various speeds. Improvements in the reliability and the speed of operation of the system now must be made.

The main problem with the device is the control system. The timing of the device is critical to its success. Specifically, it has been shown that the light sensor time, the delay time of solenoid activation and the time of solenoid activation are the critical control variables of the system. The light sensor timing works properly. Unfortunately, the control system provides fluctuating delay and activation times for the solenoids. This causes frequent note jamming.

The timing problems could be solved by using a more reliable timing algorithm or a clock on the input board. The data input board used does not have a clock. The timing of the system is conducted through counting conversions that occur at a known rate. An external clock is also needed for the operation of the solenoids because the board is unable to run the conversions while the outputs are active. The combination of these two limitations in the control system result in unreliable skew correction.

The device has potential for use in the ABIO machine. With further testing and development, the speed of the correction system should increase. If the system reliably operates at ten notes per second, it will significantly improve the performance of the ABIO. The cost of the prototype system was about $90 in mechanical hardware (not including components the ABIO already has). In bulk, this cost will decrease to near $50; possibly less. Thus, for an additional cost of about $55, the skew correction system could be added to the ABIO. This figure does not include changes that may be required within the ABIO. The control system necessary for the device may influence this price (depending on the usefulness of the ABIO computer for skew correction control). With continued experimentation and refinement of the mechanism, an effective skew correction system for the ABIO may be produced.

# Appendix A
# The Yen

The Japanese Yen is the bill that the ABIO machine handles. To understand the machine and the test apparatus, it may be useful to know the exact details of the bill. A detail that many Americans may not be familiar with is the water mark in the center of the bill. When the bill is held up to a light, a figure may be seen within the bill that normally is not visible. The properties of this mark are used by the optical recognition device (BRD) of the machine to identify bills. The ink that the bill is printed with has magnetic properties. This characteristic also serves as an identity check for bills. A third identifying mark for the bill are its dimensions (also sensed by the BRD). The dimensions of the Yen are given in Table A-I.

Table A-I: Dimensions of the Yen

| | 1,000 YEN | 5,000 YEN | 10,000 YEN |
|---|---|---|---|
| width | 76mm | 76mm | 76mm |
| length | 150mm | 155mm | 160mm |
| thickness | 0.1mm | 0.1mm | 0.1mm |
| mass | - | - | 1g +/- 10% (humidity) |

In general, Yen are in much better condition than American bills because they are circulated for a shorter period of time. Despite this, there still may be inconsistencies among bills. These variations must be considered because the ABIO must handle both new and used bills. Signs of wear include folds, tears and wrinkles. All of these factors decrease the reliability of bill handling. [Omron 90]

During testing of the de-skewing device, real Yen were not used due to the inconvenience of keeping large sums of cash in the laboratory. Instead, a set of test notes was used. The test notes share the dimensions of real Yen but are blank except for one color to indicate their denomination (and length). A test note is shown in Figure A-1

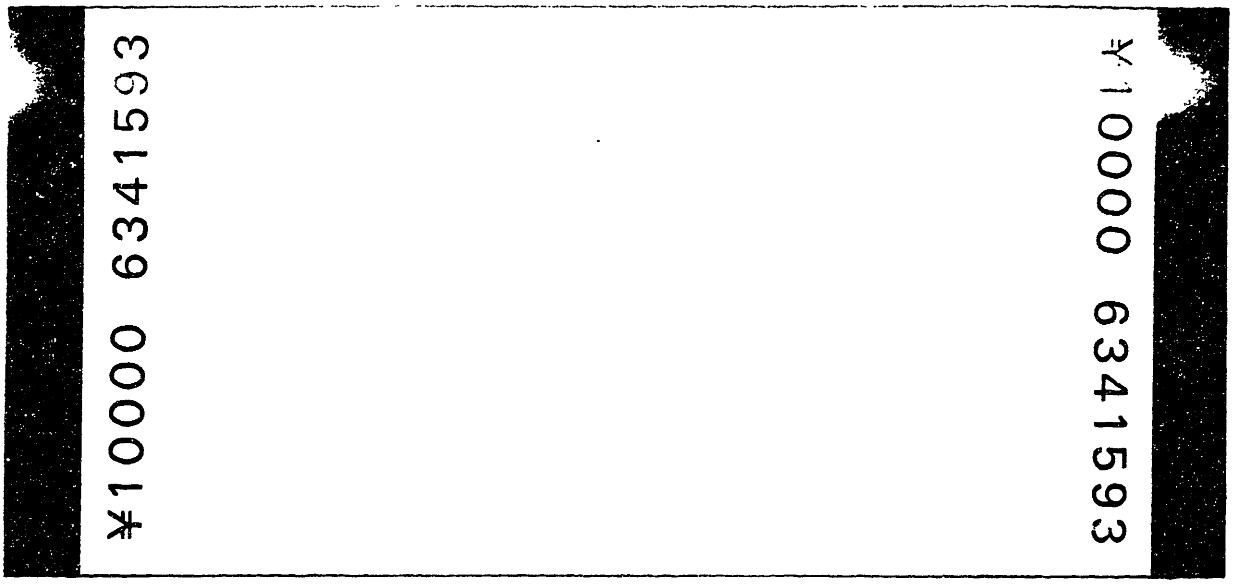


Figure A-1: A 10,000 Yen Test Note

# Appendix B

# ABIO Belt Transportation System

Bills are transported within the ABIO by a system of rubber belts. Each belt forms a loop and is ten millimeters wide. Four belts comprise a belt system. The four belts operate in pairs; there is an upper and a lower belt for each pair. The pairs are separated so the bill is held near its ends. A bill travels "sandwiched" between the upper and lower belts. During installation, the belts are stretched between pulleys of varying diameters. The belts are ten percent longer in the stretched condition. The pulleys range in size and purpose. Free spinning pulleys are usually 19mm (dimensions indicate the diameter of a pulley). There are also 15mm free spinning pulleys. At points where the bill is in contact with the pulley around a sharp turn, a 38mm pulley is used. Within each belt system, there is one drive pulley. This 28mm pulley is fixed to its shaft. The shaft interfaces with a drive gear powered by a drive belt system. The pulleys have a radius of curvature of 35mm about their axis to keep the belts aligned properly as shown in Figure B-1. The free spinning pulleys are mounted on 8mm diameter shafts 190mm (+/- 0.2mm) in length. The pulleys are spaced on the shaft such that the belts are spaced 80mm and are centered along the 190mm length of the shaft. Finally, the drive pulleys are mounted on 10mm shafts. Each drive shaft has two 19mm (O.D) bearings to allow it to rotate freely with respect to the mounting frame. [Omron 90]

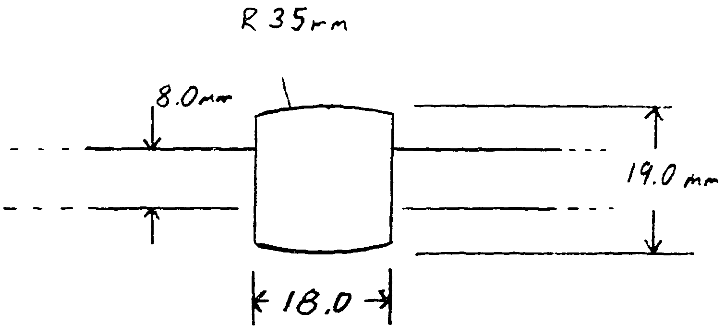


Figure B-1: Dimensions of ABIO Pulleys

# Appendix C

## Omron's Bill Recognition Device Test Apparatus

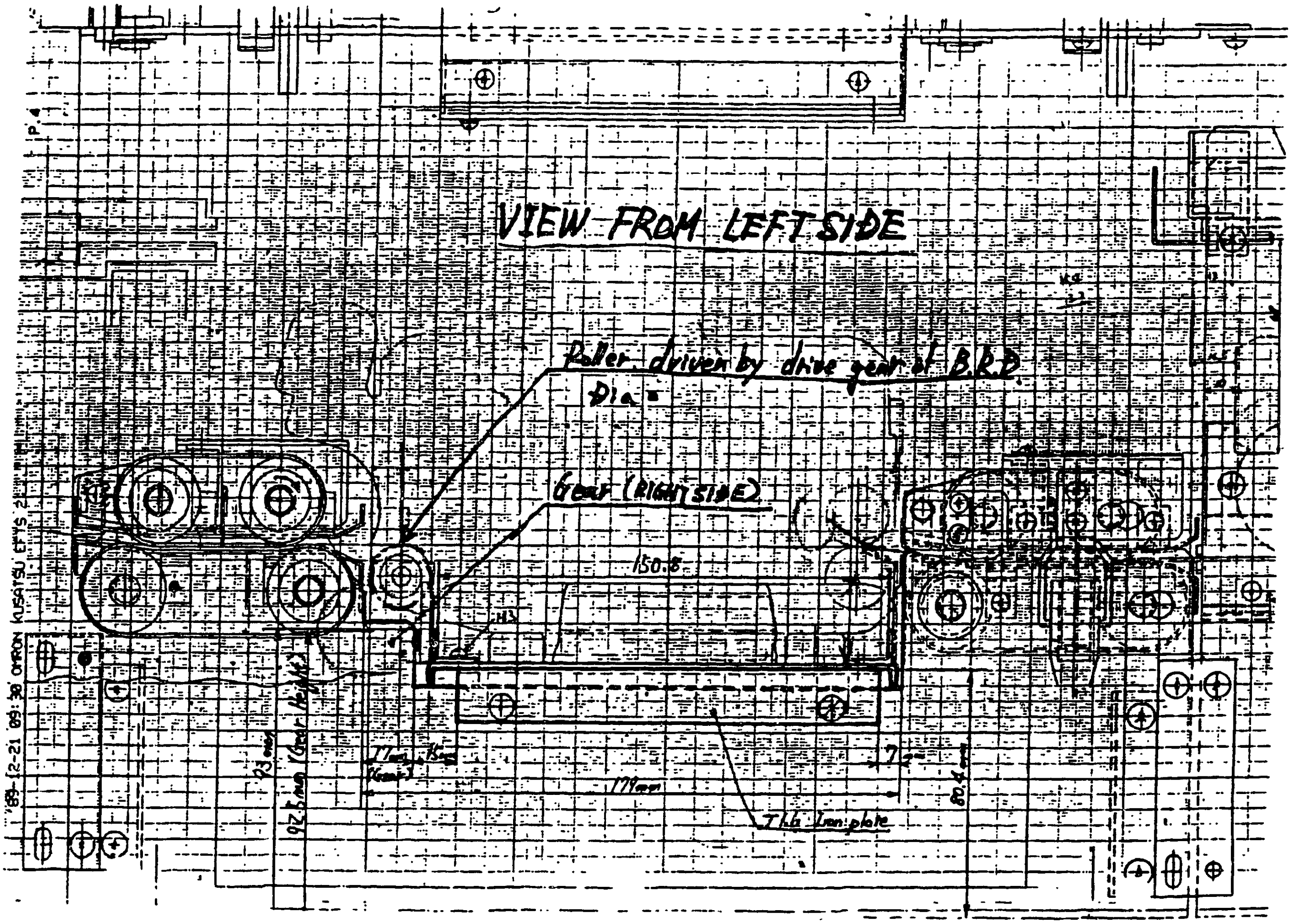


Figure C-1: Side view drawing of the BRD test apparatus [Omron 90]

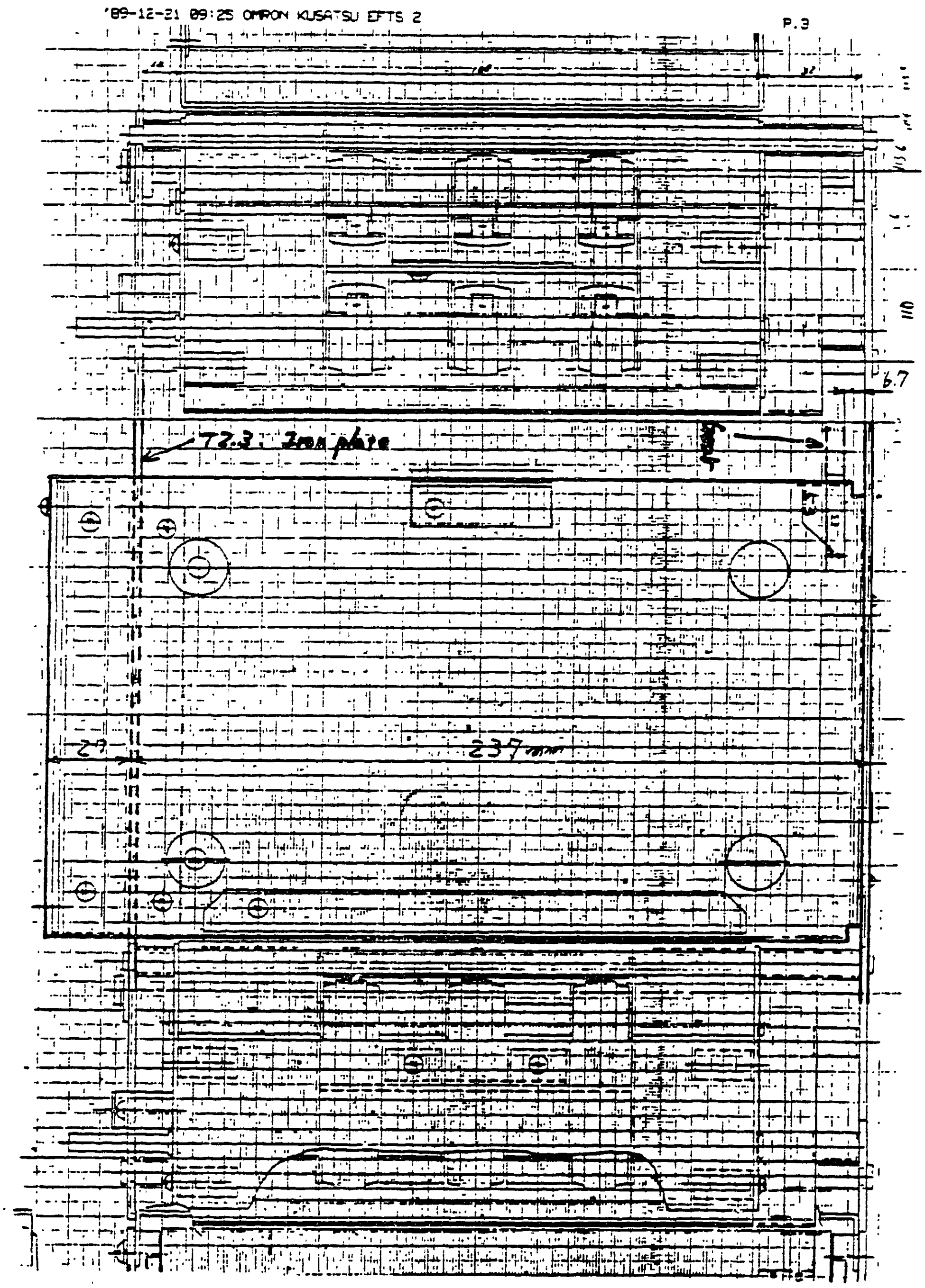


Figure C-2: Top view drawing of the BRD test apparatus [Omron 90]

# Appendix D

## Parts List and Drawings of the Belt System for the Test Section

Table D-I: Parts List

| PART | QUANTITY |
|---|---|
| 19 mm diameter pulleys with shaft | 6 |
| 19 mm diameter fixed drive pulley | 2 |
| drive shaft with 14.4mm drive gear | 1 |
| 362mm belt (unstretched) | 2 |
| 366mm belt (unstretched) | 2 |
| 171mmx105mmx3mm side plates | 2 |

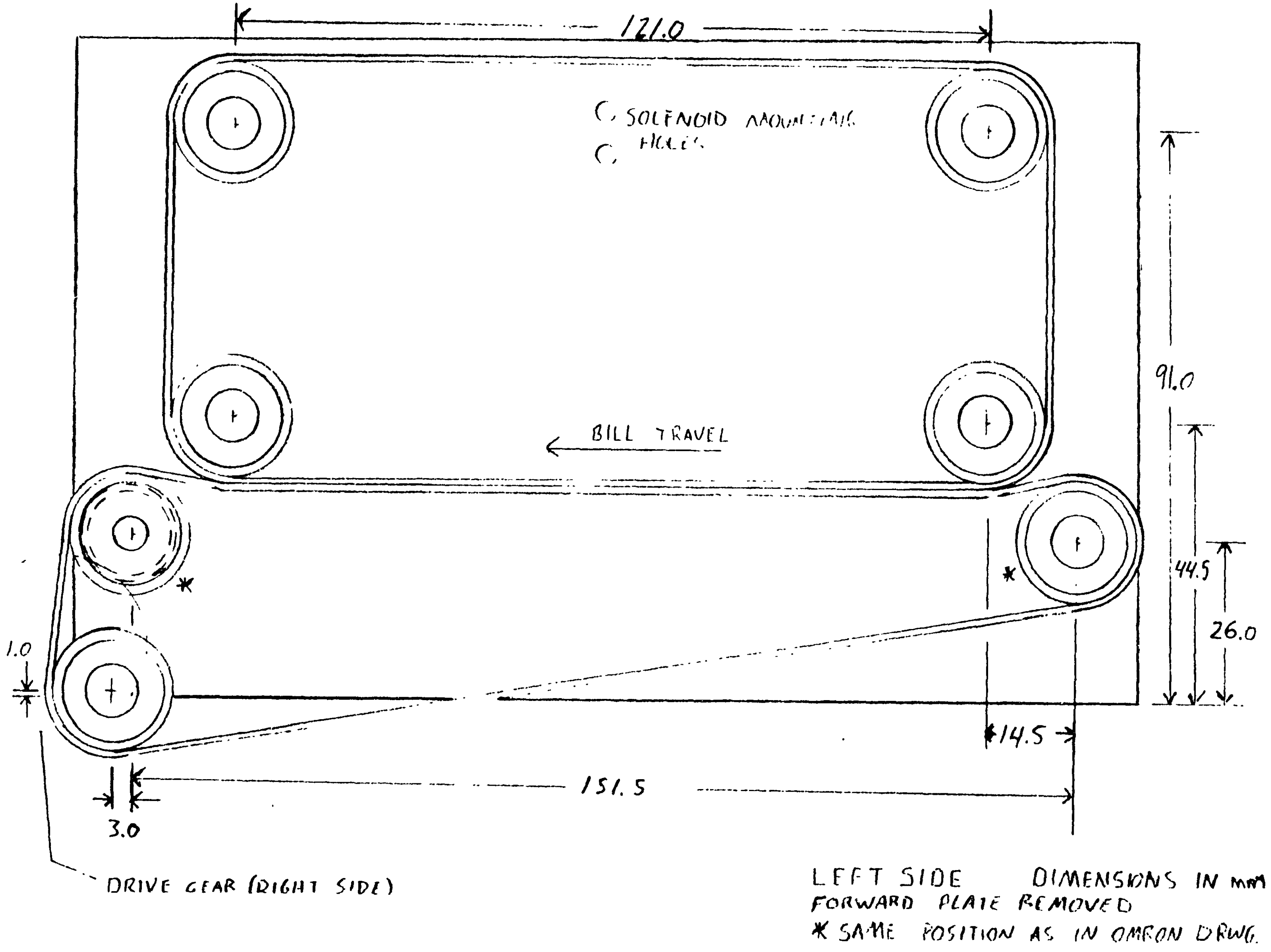


Figure D-1: Side view of the test section belt system

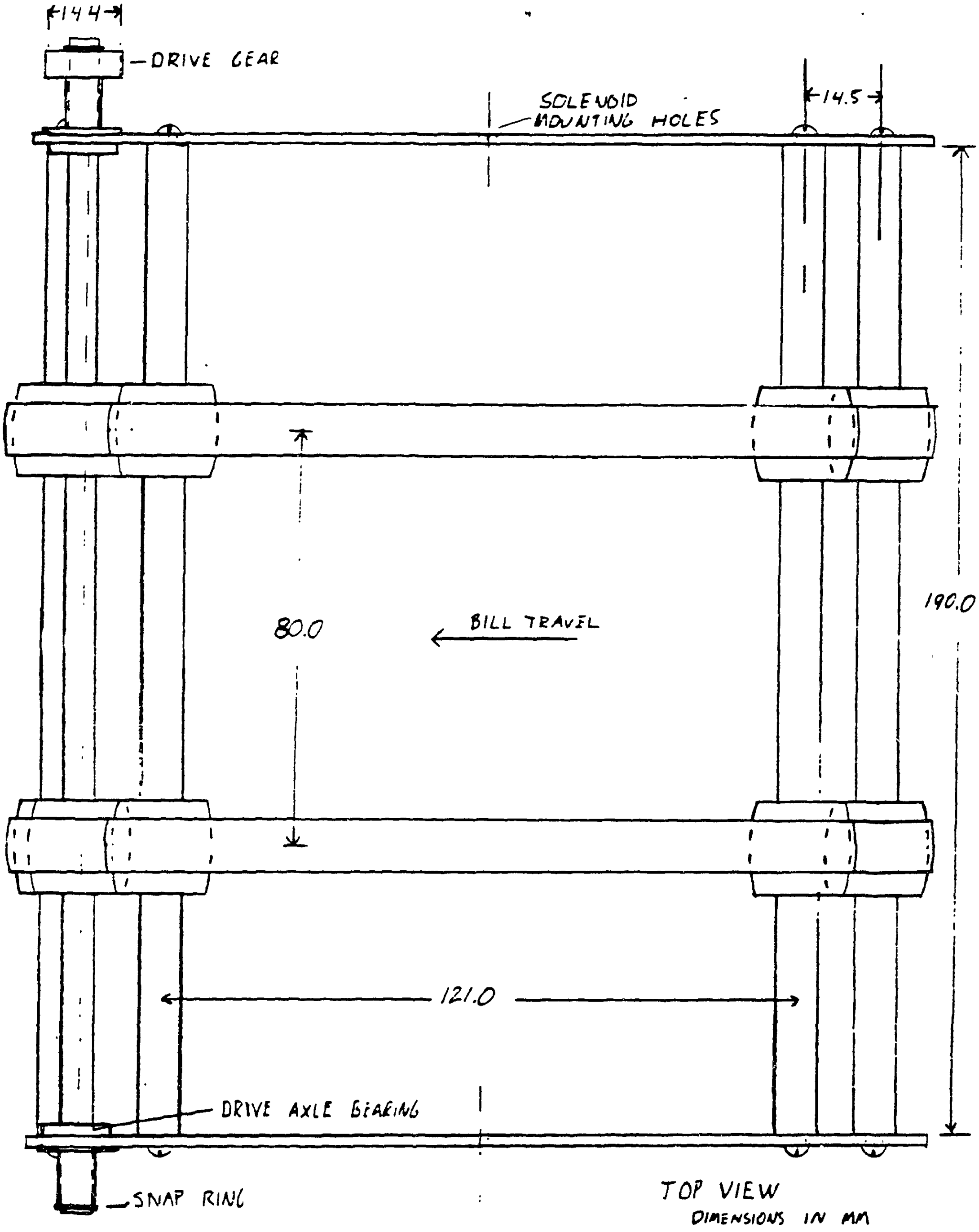


Figure D-2: Top view of the test section belt system

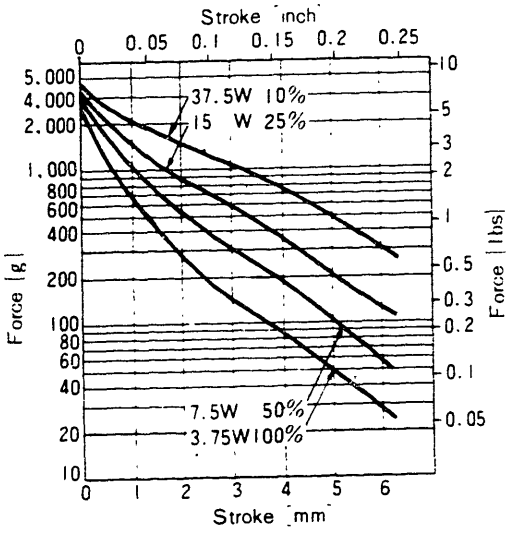
# Appendix E

# Solenoid and Relay Specifications

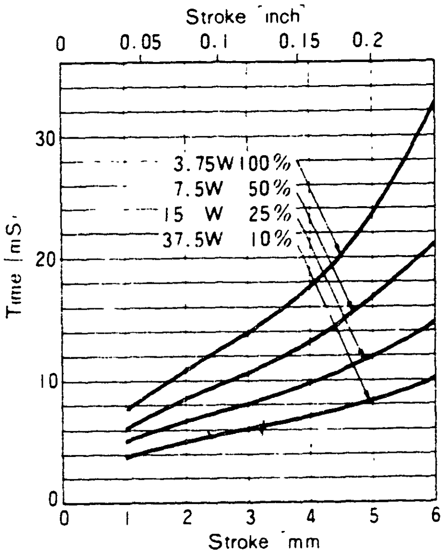
Table E-I: Specifications of Solenoids [Shindengen 90]

| | |
|---|---|
| **Manufacturer** | **Shindengen Electric** |
| **Part Number** | **F224C-12V** |
| **Cost** | **$28.43** |
| **Dimensions** | **28mm long x 22.3 mm diam.** |

Table E-II: Characteristic Diagrams for the Shindengen 224C Push/Pull Solenoid [Shindengen 90]



Stroke-Force (at 20°C)



Stroke-Time (no load at 20°C)

## Table E-III: Coil Data for the 224C-12V Solenoid [Shindengen 90]

| Type | | | | | |
|---|---|---|---|---|---|
| | duty cycle $= \frac{\text{"on" time}}{\text{"on" time} + \text{"off" time}} \times 100\%$ | 100% | 50% | 25% | 10% |
| | | continuous | intermittence | | |
| | [*1] MAX "on" time in seconds | | 100 | 36 | 7 |
| | watts at 20°C | 3.75 | 7.5 | 15 | 37.5 |
| | resistance (Ω) ± 5% at 20°C | Volt DC | | | |
| F224C-3V | 2.3 | 3 | 4.2 | 6 | 9.5 |
| F224C-6V | 10 | 6 | 8.5 | 12 | 19 |
| F224C-12V | 38 | 12 | 17 | 24 | 38 |
| F224C-24V | 167 | 24 | 34 | 48 | 76 |

[*1] *"on" time: length of the longest single impulse during one cycle.*

## Table E-IV: Specifications of Solid State Relays [Newark 89]

| | |
|---|---|
| **Manufacturer** | **Potter & Brumfield** |
| **Part Number** | **75f004** |
| **Cost** | **$11.34** |
| **Dimensions** | **1.7"x0.6"x1.25"** |
| **Typical Input** | **9mA 5 VDC** |
| **Max. Load** | **3A 60VDC** |

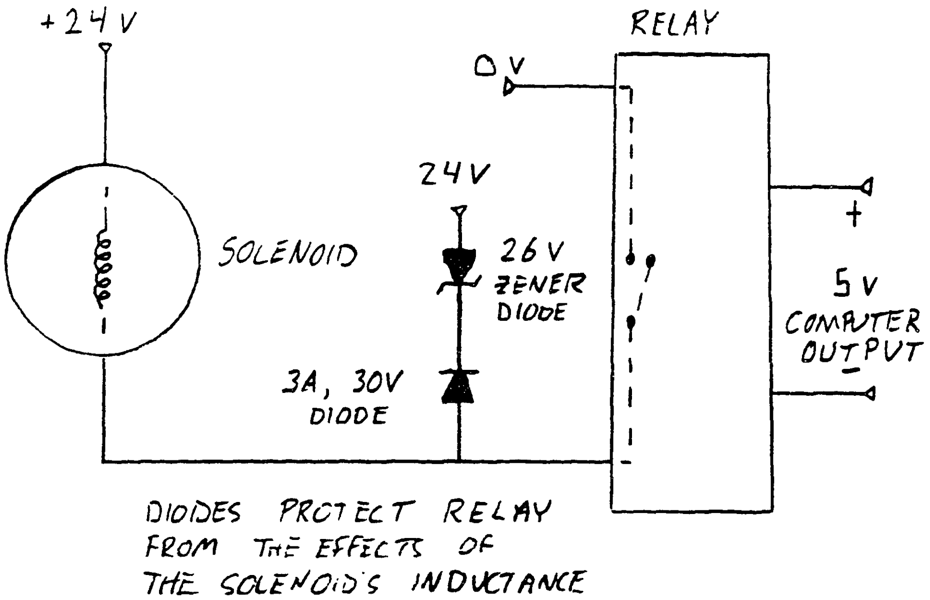


Figure E-1: Solenoid circuit diagram

# Appendix F

# Optical Sensors

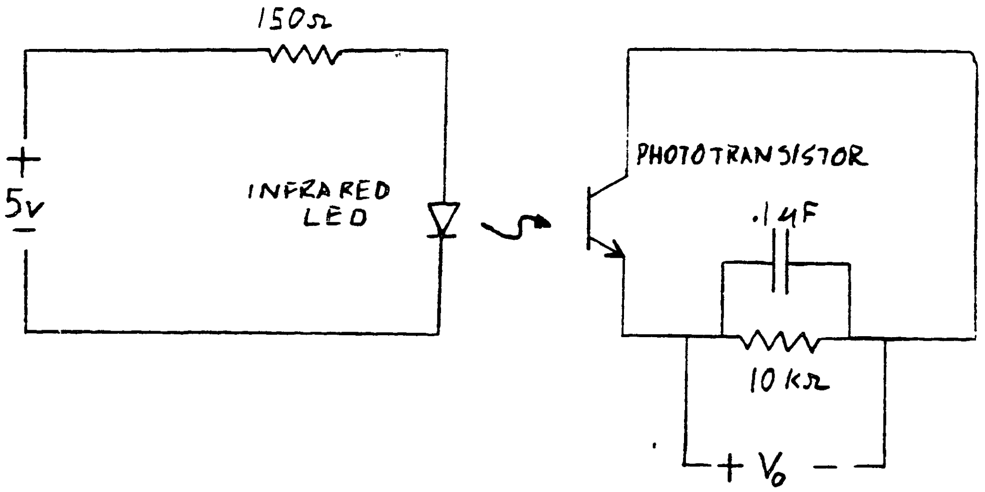


Figure F-1: Infrared LED and phototransistor circuit [Omron 90]

Table F-I: Optical Sensor Specs [Omron 90]

| | **INFRARED LED** | **PHOTOTRANSISTOR** |
|---|---|---|
| **Manufacturer** | **-** | **Omron/Sharp** |
| **Distributor** | **Solid State Sales** | **-** |
| **Part Number** | **MLE D92** | **M601P** |
| **Cost** | **$0.40** | **$2** |

# Appendix G

# Tachometer

Table G-I: Tachometer Specifications [Servo 90]

| | |
|---|---|
| **Manufacturer** | **Globe** |
| **Dealer** | **Servo Systems Co.** |
| **Part Number** | **22A520** |
| **Cost** | **$19.50** |
| **Output Voltage** | **0.7 Volts/1000 RPM** |
| **Driving Torque** | **0.7 oz-in. at 1000 RPM** |
| **Length** | **40mm** |
| **Diameter** | **30mm** |

Tachometer conversion factor to determine the speed of the bill:

$$\text{Bill Speed} = (V_{tach})(0.7\ \text{V/1000 RPM})^{-1}(2\pi\ \text{rad./rev})(1\ \text{min/60s})(14\text{mm pulley radius})$$

Evaluating this equation gives:

$$\text{Bill Speed} = 2094.4V_{tach}\ \text{mm/sec} \tag{1}$$

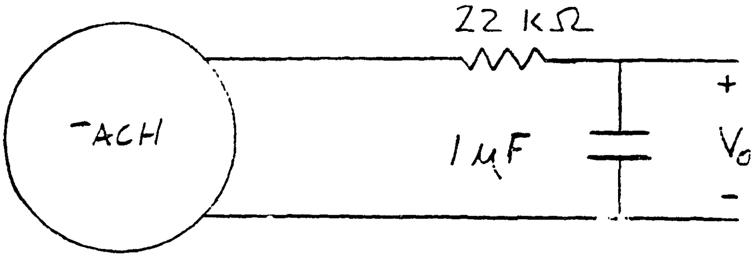


Figure G-1: Tachometer circuit diagram

# Appendix H

# Data Acquisition Board

## Table H-I: Features of the DT2811PGL Data Acquisition Board [Data 90]

- IBM® PC/XT/XT-compatible board featuring 20kHz A/D, two 50kHz D/As, 8 digital input lines, 8 digital output lines, and programmable pacer clock
- A/D features
  - 20kHz throughput
  - 12-bit resolution
  - Programmable gains of 1, 2, 4, 8 (DT2811-PGH)
  - Programmable gains of 1, 10, 100, 500 (DT2811-PGL)
  - 16SE/8DI channels
- D/A features
  - 50kHz throughput per DAC
  - 2 independent DACs
  - 12-bit resolution
  - Outputs are short-circuit protected
- Digital I/O
  - 8 lines of digital input
  - 8 lines of digital output
- Support for four-level bus interrupt
- I/O compatible with DT2801 Series boards to ensure pin-compatibility with wide range of screw terminal panels and signal conditioning products
- Optional subroutine library (LPCLAB™) and third party application software packages
- Shipped with comprehensive user manual which includes programming instructions

| | ANALOG INPUTS | | | | ANALOG OUTPUTS | | DIGITAL FUNCTIONS | |
|---|---|---|---|---|---|---|---|---|
| MODEL | Channels | Resolution (bits) | Input Ranges | Thruput (kHz) | Channels | Thruput (kHz) | I/O Lines | Pacer Clock |
| DT2811-PGH | 16SE/8DI | 12 | 0–.625,1.25,2.5,5V<br>±.31,.625,1.25,2.5,5V | 20 | 2 | 50/chan | 8 In<br>8 Out | ✓ |
| DT2811-PGL | 16SE/8DI | 12 | 0–.01,.05,.5,5V<br>±.005,.01,.05,.5,5V | 20 | 2 | 50/chan | 8 In<br>8 Out | ✓ |

# Appendix I

# Hardware Trigger

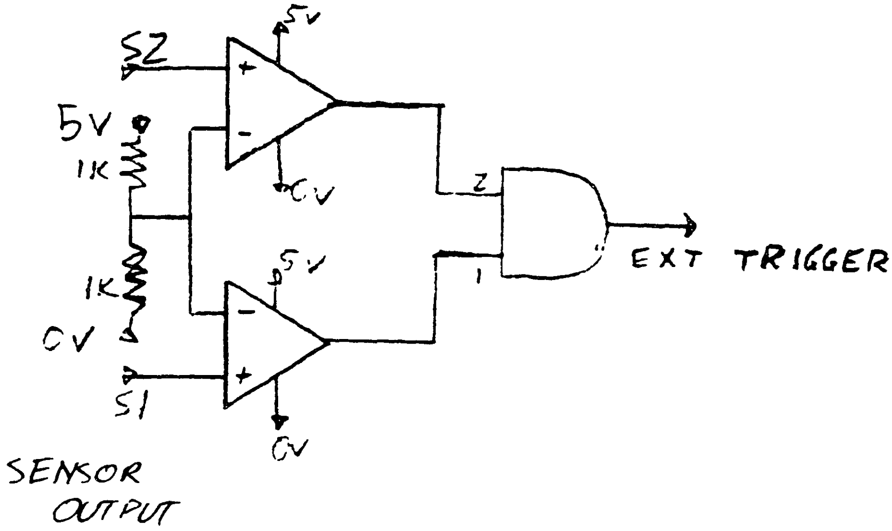


Figure I-1: Circuit diagram for the hardware trigger [Omron 90] and [Levinsky 90]

# Appendix J
# Note Buckling

While a solenoid is pinching a bill, the bill experiences various forces. Some of the forces are a result of the belt's translation with respect to the bill. Other forces are caused from the bill's rotation with respect to the belts.

The belts (upper and lower) closest to the solenoid slide over the bill during skew correction. There is a drag force ($F_d$) along the direction of the belt due to this sliding motion, see Figure J-1. The force $F_d$ is given in equation 1, where $F_{bpf}$ is the belt pinch force and the friction is between the bill and the belt.

$$F_d = F_{bpf} \times \mu_{kinetic} \tag{1}$$

Either decreasing the belt pinch force or using an alternate belt material will make skew correction less stressful for a bill. Balancing the forces in the Y direction (the bill does not move in the Y direction underneath belt one), shows that the solenoid force, $F_s$, is approximately equal to $F_d$. The error of this approximation is $F_{d2}$ which we know to be small from a moment balance (assuming the rotational velocity of the bill is constant).

$F_d$ compresses the section of the bill above the line of rotation in the Y direction (the direction of $F_d$). The compressive forces are strongest near the solenoid and belt one. The line of rotation connects the solenoid pivot point and the second point of rotation. The second point of rotation is the point where the note rotates with respect to belt two. The location of this point changes during the straightening of the bill but for purposes of this example, it will be assumed to be directly to the right of the solenoid. Compressive forces in the plane of the bill (this page) cause buckling because the bill is not stiff in this dimension. To prevent buckling, the compressive forces should be minimized. Thus, the solenoid should be placed as near the upper edge of the bill as possible to minimize the area

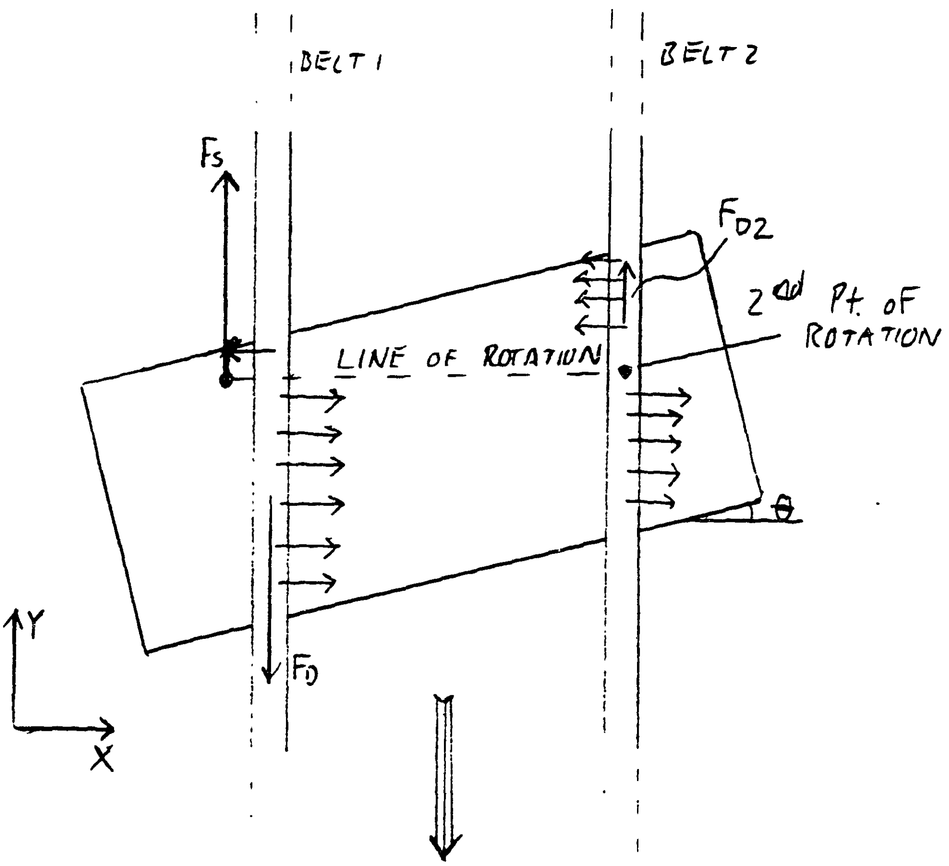


Figure J-1: Free body diagram of bill during skew correction

of the bill above the line of rotation. The portion of the bill below the line of rotation (especially near belt one) is in tension along the Y direction (the direction of $F_d$).

The tendency of the bill to buckle due to these vertical forces is decreased by the belt pinch force. The belts brace the bill along their length. To buckle, the bill would have to force the upper and lower belts apart. A problem exists at the edge of the bill though. As belt one quickly slides over the edge of the bill, the belt tends to grab the edge (especially if the edge is bent). Effectively the belt tries to "peel" the bill over itself, initiating a buckling behavior. Again, by placing the solenoid near the edge, this problem is avoided. Forces in the X direction also initiate buckling behavior.

The forces in the X direction (shown in Figure J-1) are caused from the rotation of the bill with respect to the belts. The compressive forces in the X direction are responsible for the bowing (or buckling) problem discussed in Chapter 5. These forces are directly proportional to the belt pinch force ($F_{bpf}$) and the friction between the bill and the belt ($\mu_{kinetic}$).

# Appendix K

## Initial Control Program [Levinsky 90]

```
include <math.h>     /* include math function definitions             */
#include <conio.h>    /* include i/o function definitions              */
#include <stdio.h>    /* include standard I/O file                     */
#include <stdlib.h>   /* include standard library file                 */
#include "lpclerrs.h" /* include LPCLAB error codes                    */
#include "lpcldefs.h" /* include LPCLAB function declarations          */

#define arraylength 1000
#define frequency   2000

main()
{
unsigned short returnval;                /* Returned value from routines.   */
unsigned short returnarray[arraylength]; /* Continuous A/D return array.    */
unsigned short threshold;  /* Digital value of obscuration voltage. */
unsigned short begintime;  /* First measured timer value.           */
unsigned short endtime;    /* Final measured timer value.           */
unsigned short difftime;   /* Difference between begin. and end.    */
short directionflag;       /* 0 = Ch. 0 obscured first, 1 = Ch. 1   */
short counter;             /* Loop variable.                        */
short number;              /* For test_adc routines                 */
short coverconversion;     /* Conversion where both are covered     */
short covertimerval;       /* Timer value at cover                  */
short lowerlimit;          /* Used in array-search algorithm        */
float elapsed_time;        /* Time since both were covered          */
float velocity;            /* Speed of notes                        */
float wait_fire;           /* Time until fire of solenoid           */
float wait_lift;           /* Time until lift of solenoid           */
float final_wait;          /* Final wait to be sure bill is clear   */

lp_initialize();
lp_select_board(1);
lp_set_timeout(20);
lp_disable_system_clock();
lp_dac_value(0,0);             /* Clear system of all possible errors */
lp_dac_value(1,0);
lp_stop_adc();
lp_set_clock_frequency(500); /* Slow down for velocity calculation */
threshold = 2000;
velocity = 0;

for (counter = 1;counter <=100;counter++)
  {lp_adc_value(4,10,&returnval);
   velocity = velocity + returnval;}
velocity = velocity/100;
velocity = 0.5*(velocity/4096.0) * (1000/(0.7*60)) * 2*3.1415927 *.028;
printf ("Velocity = %f\n",velocity);
wait_fire = .070/velocity-4*.001;


lp_set_clock_frequency(frequency);

while( !kbhit() )
{
   /*    Initialize returnarray, coverconversion so we can start anew.  */
   /*    If Ch. 0 is low, it's obscured, and directionflag = 0.         */

   coverconversion = 0;
   for (counter = 0; counter <= arraylength-1; ++counter)
   returnarray[counter] = 5555;  /* Fill array with dummy values */
```

```
/* 1. Check Channel 0 when we get a trigger (AND of the two sensors) */
/*    If Ch. 0 is low, it's obscured, and directionflag = 0.          */

lp_setup_adc(1,0,1,1);
lp_burst_adc(arraylength,&returnarray);
Wait:
lp_test_adc(&number); /* See if conversion started */
if(number==arraylength) goto Wait;
if (returnarray[0]<= threshold) directionflag = 0;
if (returnarray[0]>  threshold) directionflag = 1;
printf("Initial coverup is on channel %d\t", directionflag);

/* 2. Continue observing obscuration by looking at filling matrix.    */
/*    Determine time difference by knowledge of clock period.         */

BothCovered:

lp_test_adc(&number);
if (arraylength>40+number) lowerlimit = arraylength - number - 40;
   else lowerlimit = 0;
for (counter = lowerlimit;counter<=arraylength-number;++counter)
  {if ( (returnarray[counter -1]<threshold) && (returnarray[counter -2]<thres
      {coverconversion = counter -1;
       goto Skew_calculate;}
  }
if (number==0)
     {printf("End of conversions.\n");
      goto Printout;}

if (coverconversion == 0) goto BothCovered;

/* 3. Calculate time until throw of solenoid. Check timer and wait.   */

Skew_calculate:

lp_test_adc(&number);
if ( ((arraylength - number - coverconversion)*.0005) < wait_fire )
  goto Skew_calculate;

/* 4. Throw proper solenoid. Check timer and wait until end of throw.*/

lp_stop_adc();
wait_lift = 3*coverconversion*0.0005;  /* Wait equal time */
lp_input_digital_value(0,255,&returnval);
covertimerval=returnval;
if (directionflag == 0) lp_dac_value(0,0x0FFF);
  else lp_dac_value(1,0x0FFF);

/* 5. Unthrow solenoid. Goto 1.                                       */

Lift_solenoid:

lp_input_digital_value(0,255,&returnval);
elapsed_time = (returnval - covertimerval)/900.0;
if (elapsed_time <= 0) elapsed_time = elapsed_time + 255/900;
if ( (elapsed_time < wait_lift) ) goto Lift_solenoid;
if (directionflag == 0 ) lp_dac_value(0,0);
   else lp_dac_value(1,0);
```

```
   Short_wait:    /* To be sure bill has cleared sensors */

   lp_adc_value(5,1,&returnval);
   if (returnval <= threshold) goto Short_wait;  /*One sensor covered */

   Printout:

   printf("Both are covered at conversion %d\n", coverconversion);
   /*for (counter = 0;counter<19;counter=counter+2)
   printf("Channel 0 value %d Channel 1 value %d\n",returnarray[counter],
   returnarray[counter+1]); */
  }
lp_stop_adc();
lp_enable_system_clock();
lp_terminate();
}
```

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