Senior EE Engineering Design Capstone Project
EE-490

Detroit Pinball Machine
Professor Kenneth Kaiser
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Project Requirements and Specifications

1. Four electromagnets
    a. Similar to 'Flying Aces,' heat sink, duty cycle
2. Ball chute
    a. Use drywall screen or u-channel
3. PLC controlled
4. Commercial plunger
5. Either two commercial or hand-made (similar to 'Gangster') paddles
6. Push-button for control of magnet near right paddle control
7. Loose ball at one hole behind paddles
8. Three balls per game
9. Buzzer or other primitive non-electronic sound when scoring
10. Painted, decorated according to a theme top, no decals
11. Nails
    a. Similar to 'Gangster,' straight, strong, 150, playability
    b. REMINDER: pre-drill
12. Solid non-plywood sides (see 'Gangster')
    a. See 'Gangster for mounding and corner
13. Single commercial power supply
14. Power control through switch on power cord
15. Professional wiring and connectors
16. No tape or glue with wiring
17. Do not drop balls directly on switches
18. Provide me with 2 extra balls
19. Professional physical and electrical construction practices
20. No screws present/seen from outside
21. Overheating protection
    a. Thermal cutoff
22. Wood exterior painted
    a. No glue marks
    b. Don't paint inside
23. H field zones marked or indicated
24. Point values for holes indicated
25. No obvious toy modifications
26. One or two ramps with a function
27. Other non-PLC electronics on a professional board
28. Robust
    a. Will be continually tested for 1 hour
        i. No stuck balls
        ii. No breakdowns
29. No additional fans or cooling systems besides those on power supply
30. Two antique handles per side
31. 5 scoring holes
    a. Opening must be fillet
32. No plastic on the outside
33. Need to have a ball catcher
34. Dimensions
    a. 22" x 40" x 10-12"
35. Table top: no legs
36. Fill in nail holes
37. Reset control
38. More than 5 scoring lights, 1 power light1 game over light
39. No plastic seen except top
40. No stuck balls
41. Bell scoring
42. Electromagnetic strong enough to hold ball in place
43. Use standard pin-ball
44. No backs
45. Theme the game
46. Twisted wire not solid-core
    a. Except magnet wire
47. No tape
48. Engineering standard incorporated
49. Magnet touchable/grab able at any time by instructor
50. No direct access to fan-blades on power-supply
51. Work with 1/2" offset on either side of machine
52. Three or more rubber-band bumpers
53. Out channel needed

Detroit Pinball Machine Pictures

Figure1. Top of Pinball Machine

Detroit Pinball Machine Pictures

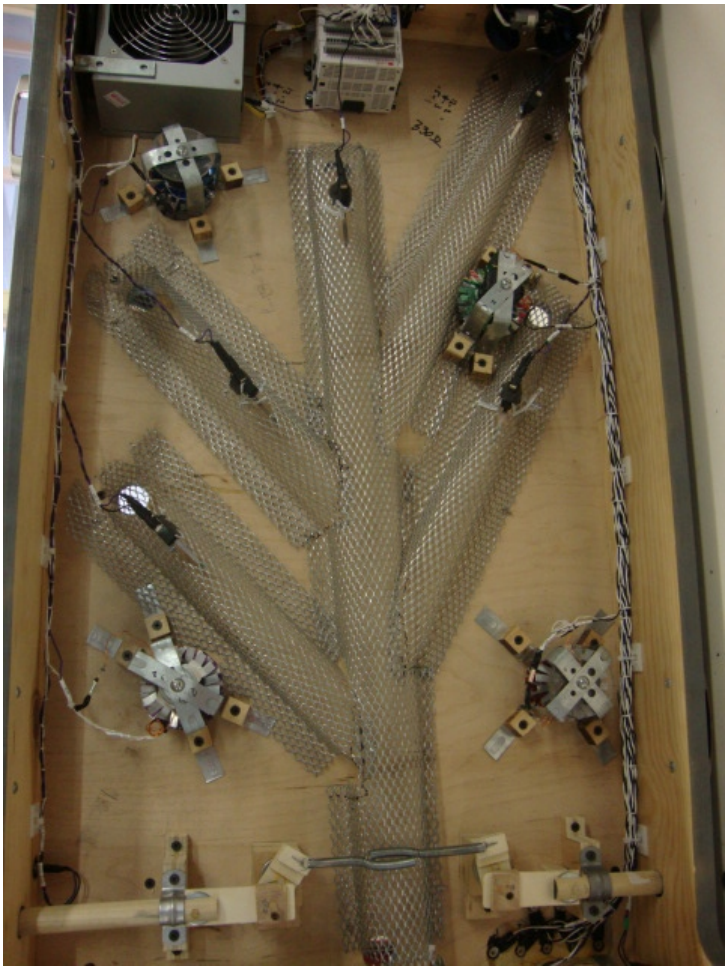


Figure2. Bottom of Pinball Machine

Incorporated Engineering Standard

IPC J-STD-001D
Requirements for Soldered Electrical and Electronic Assemblies

IPC-A-610D
Acceptability of Electronic Assemblies

We used these standards for a basis of assembly and inspection of all soldered and crimped connections. Each connection and wire was treated and inspected to be compliant with the Class 2 criterion; which is the level of high-end commercial electronics and test equipment.

IPC is made up of industry members around the world whose mission it is to create standards and practices for electronic interconnectivity. The standards they release are sanctioned by ANSI and the DoD, and are requirements on all government contracts.

Examples of the criteria that we followed per IPC J-STD-001D, IPC-A-610D are:

All wires that were stripped showed no nicks or damaged strands **1**

1 Class 1-Some Allowed
Class 2-Defect
Class 3-Defect

All Soldered joints show good wetting, and shiny appearance **2**

2 Class 1- Not Est
Class 2-Defect
Class 3-Defect

All Crimped connections show no exposed wire **3**

3 Class 1-Some Allowed
Class 2-Defect
Class 3-Defect

Protection Method for Overheating and Fire Risks

In order to follow safety standards, this project required each pinball machine to incorporate a protection method for overheating and fire risks. To incorporate this method, we needed a cutoff device that would turn off all our electromagnets when it reached a very hot temperature. Our group proceeded to use a component called a thermal fuse to implement this protection method. A thermal fuse can be defined as a single-use cutoff safety device that disconnects the current to the heating component, in this case the electromagnets, to protect from component malfunctions and damage. We purchased four thermal fuses rated for 228 ° C from RadioShack and attached them in series to each electromagnet in the pinball machine. The below figures illustrate this method.

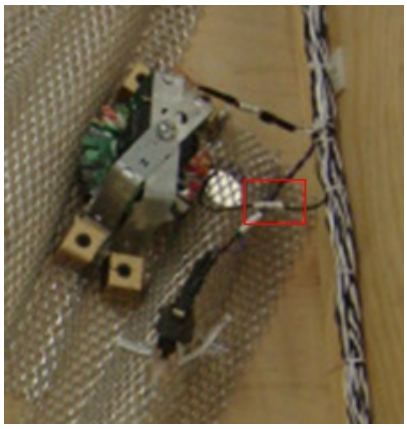


Figure 3. Thermal Fuse Attached to Magnet

Figure 4. Thermal Fuse

How to Reproduce the Electromagnets

The following information provides a detailed explanation on how to replicate the four electromagnets used in our pinball machine.

Required Materials

(1) - 12" 1018 Carbon Steel Rod Stock (1" Diameter)
(1000ft) - 22 Gauge High Temp Magnet Wire
- Washers
(4) - Aluminum cans
- Zip Ties
- Thermal Paste
- Lathe
- Electrical tape

Instructions

Coiling the Electromagnet

1. Cut the 12" Carbon steel rod into four 3" steel rods
2. Drill and ¼-20 tap holes into one end of each of the four rods. This will be used for mounting and to attach washers at the end in order to keep the copper wire coiled and in tact.
3. Chuck approximately ½" of the rod segment into the lathe, and attach a large washer opposite with a ¼-20 bolt to use as a back stop for the windings.
4. Tie copper wire at one end of the rod and leave about 4-5" extra wire hanging. This wire will be used to attach the magnet to the power supply in final assembly.
5. Turn ON the lathe at a slow speed and begin winding the copper wire onto the steel rod. Ensure that you keep the coiled wire tight between each turn.
    a. *It may be easier to use two people to coil each magnet. One person holds the copper wire. The other person uses his/her fingers or a small rod to keep the coiled wire tight between each turn.
6. When you reach the end of the rod, begin another layer and wind the copper wire to the opposite side.
7. Continue steps 5 and 6 until you have reached 10 layers of copper wire.
8. When you have completed the 10^{th} layer, leave another 4-5" extra wire hanging for the other end of the electromagnet.
9. Remove your completed electromagnet from the lathe and attach the heat-sinks
10. Repeat steps 3-9 for the remaining electromagnets

Creating and Attaching Heat-sinks

1. Cut and remove the top and bottom part an aluminum can

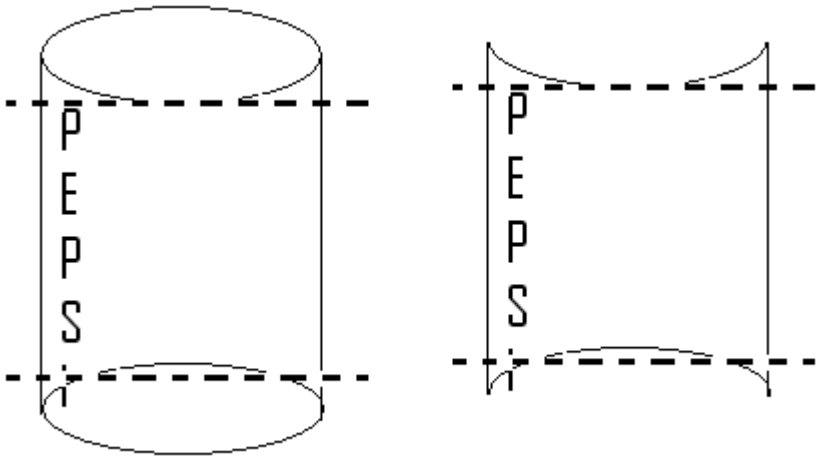


Figure 5. Step 1

2. Cut down one side of the remaining can to make the can flat
3. Cut the can down to the circumference of the magnets.

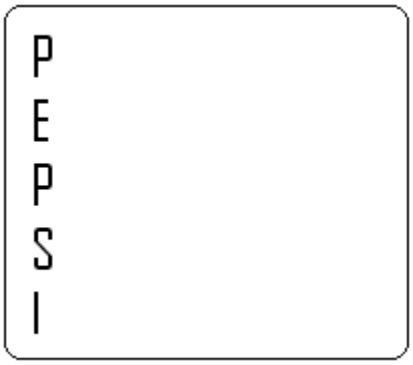


Figure 6. Step 3

4. Cut slits every ¼-½", leaving a ½" section in the middle uncut for mounting, on the top and bottom of the flat aluminum to create fins for the heat sink. See figure below.

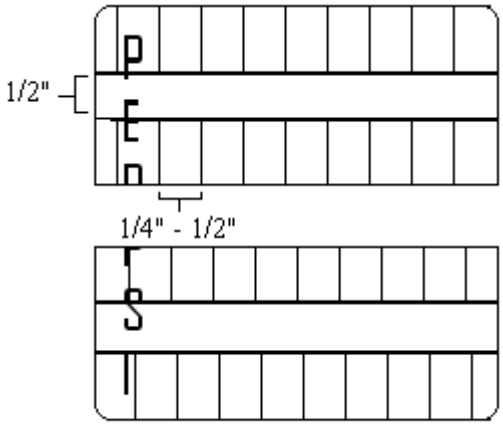
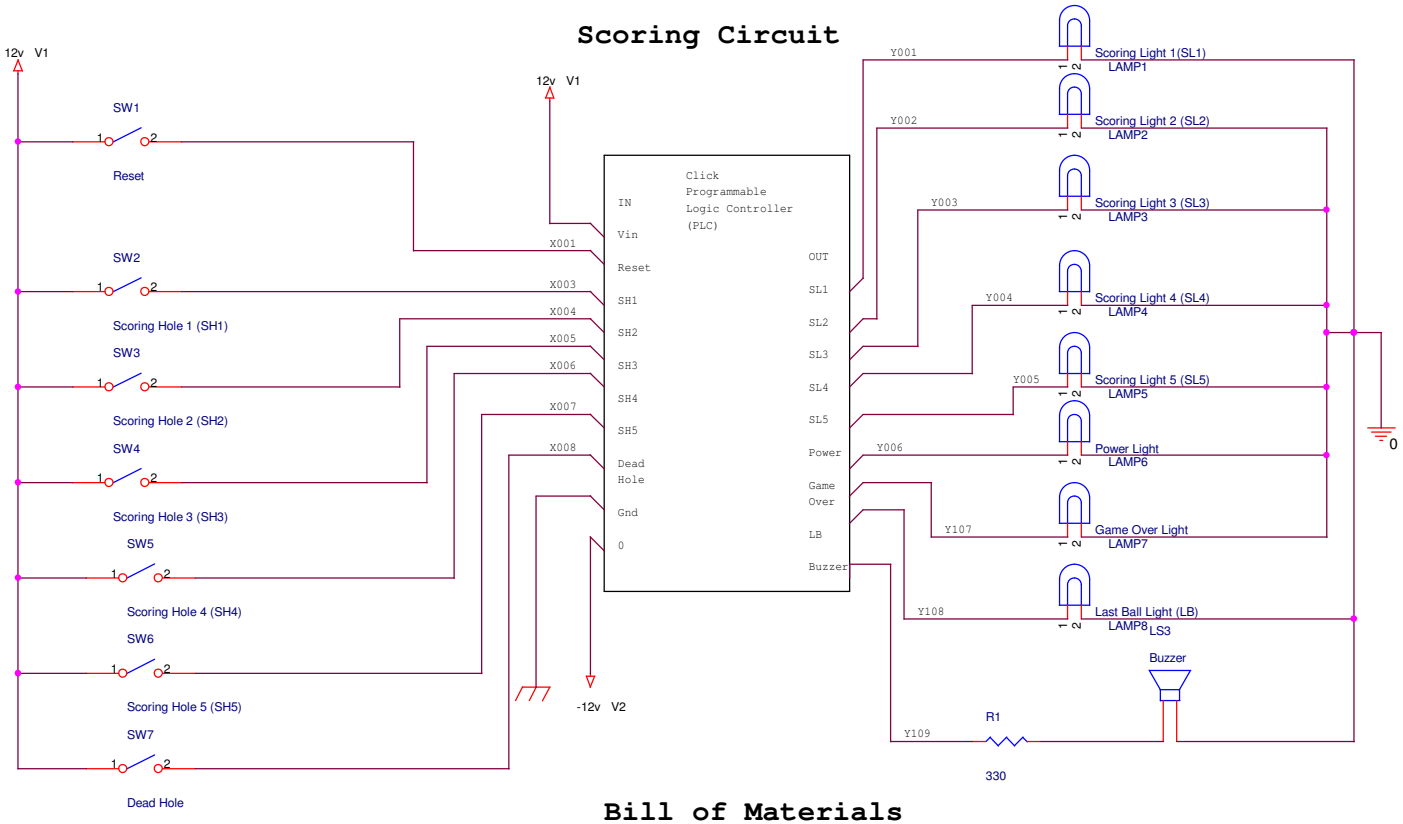


Figure 7. Step 4

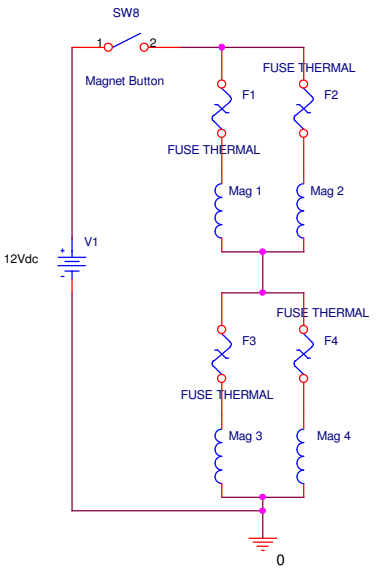
5. After cutting the fins, bend fins 90° to the mounting surface and spread thermal paste across the mounting surface of both the top and bottom heat-sinks.
6. Attach one aluminum can heat-sink to the bottom part of the electromagnet. Ensure the aluminum is touching the magnet wire directly.
7. Use a zip tie around the flat part of the heat-sink to tighten and mount it to the magnet.
8. Attach the second aluminum can heat-sink to the top part of the electromagnet. Again, ensure the aluminum is touching the copper wire directly.
9. Use a zip tie around the flat part of the heat-sink to tighten and mount it to the magnet
10. Using electrical tape, tape around the top and bottom areas of the electromagnets to ensure the magnet wire remains in tact and coiled onto the steel rod.

Figure 8. Final Electromagnet Product

Scoring Circuit



Magnet Circuit



Bill of Materials

Item Number	Component Name	Quantity	Description	Vendor	Vendor Part #	Website
1	V1,V2	1	300 Watt Power Supply Unit	Digilink Computers		www.digilinkcomputers.com
2	PLC	1	KOYO Click Series Programmable Logic Controller Built-in Discrete I/O CPU and Output Module	Automation Direct	C0-00DD2-D, C0-16TD2	www.automationdirect.com
3	SW1-SW7	7	Miniature Snap-Action Switch, Long-Hinge Lever Actuator, SPDT	Grainger	3XG46	www.grainger.com
4	SW8	1	Momentary Switch - Normally Open Switch	Radioshack	275-609	www.radioshack.com
5	Lamp1-8	8	14.4V 100mA Incandescent Flashlight Bulb	Radioshack	272-1127	www.radioshack.com
6	Lamp1-8 Sockets	8	E-10 Bayonet Base with Solder Tabs	Radioshack	272-355	www.radioshack.com
7	Buzzer	1	Alarm Clock	Target		www.target.com
8	F1-F4	4	128°C (262.4°F) Thermal Protector Fuses	Radioshack	272-1322	www.radioshack.com
9	R1	1	330 Ohm 1/4 Watt Resistor	Kettering University		
10	Mag1-4	4	Iron Core Electromagnetic Coils 3" long by 1" diameter iron core (1018 Steel Rod Stock) 0.5" of core left bare for mounting Each core has 10 layers of windings Coil wire is 22 AWG Enamel-Coated Copper Magnet Wire	Grainger	2HJF6	www.grainger.com
11		1	20 AWG Twisted Wire	Kettering University		

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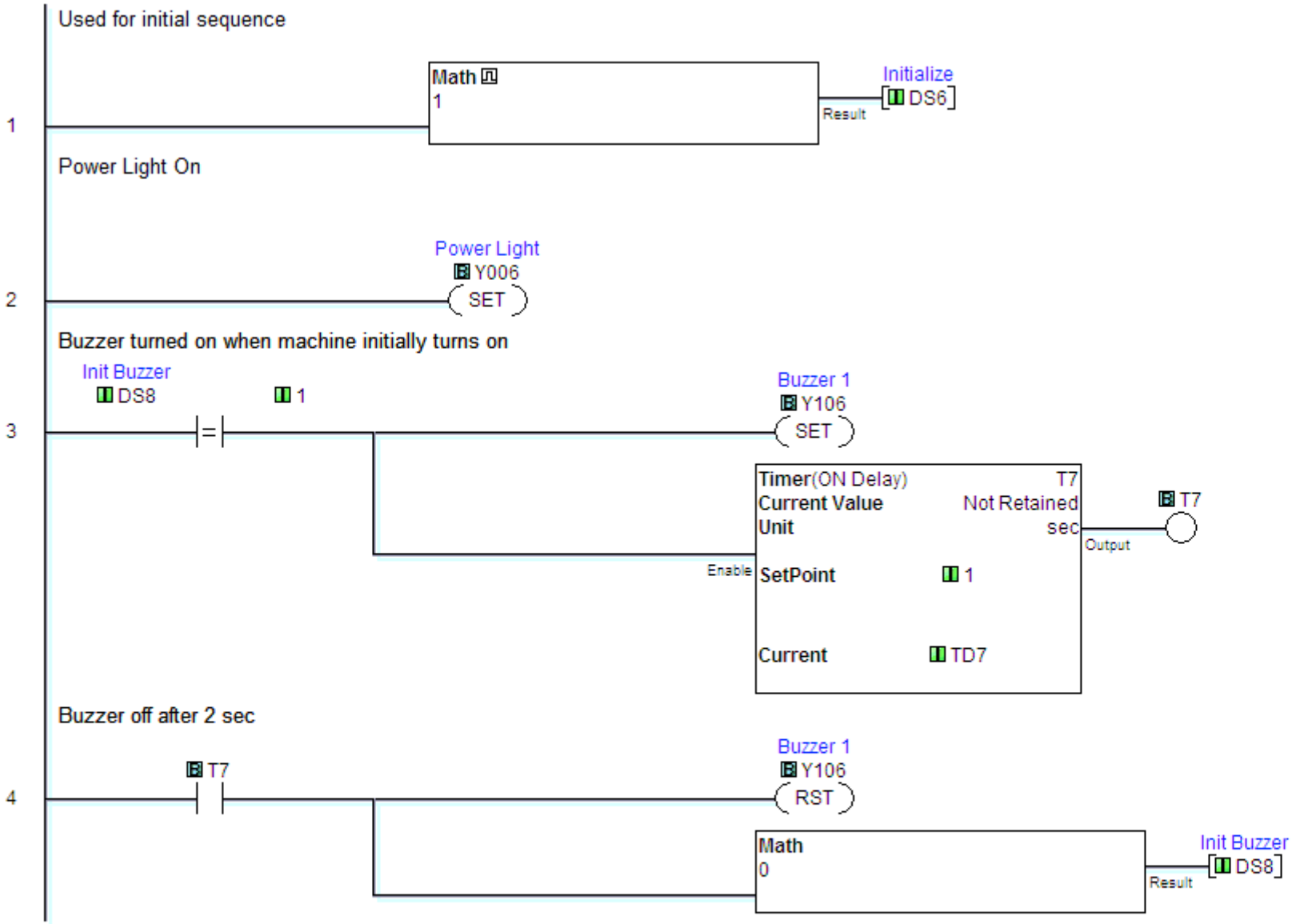
Size B	Document Number 1		Rev 1
Date: Friday, September 18, 2009	Sheet 1 of 1		


Used for initial sequence
Math
1
Initialize
DS6
Result
1
Power Light On
Power Light
Y006
SET
2
Buzzer turned on when machine initially turns on
Init Buzzer
DS8
=
1
Buzzer 1
Y106
SET
3
Timer(ON Delay)
T7
Current Value
Not Retained
Unit
sec
T7
Output
Enable
SetPoint
1
Current
TD7
Buzzer off after 2 sec
T7
Buzzer 1
Y106
RST
4
Math
0
Init Buzzer
DS8
Result

Light sequence when machine turns on

5

Initialize
DS6 = 1

Enable

Reset Button
X001

Reset

Drum (TimeBase:ms)

Step	Duration	1	2	3	4	5
1	250	■	□	■	□	□
2	250	□	■	□	■	□
3	250	□	□	■	□	■
4	250	□	■	□	■	□
5	250	■	□	■	□	□
6	250	■	□	□	□	□
7	250	□	□	■	□	□
8	250	□	■	□	□	□
9	250	□	□	□	■	□
10	250	□	□	■	□	□
11	250	□	□	□	□	■
12	250	□	□	□	■	□
13	250	□	■	□	□	□
14	250	□	□	■	□	□
15	250	■	□	□	□	□

Output
1=Y001 5=Y005 9= 13=
2=Y002 6= 10= 14=
3=Y003 7= 11= 15=
4=Y004 8= 12= 16=

New Step

Current Step — Init Seq: DS7

Elapsed Time — Init Seq Timer: TD5

Init C2
C2

Complete

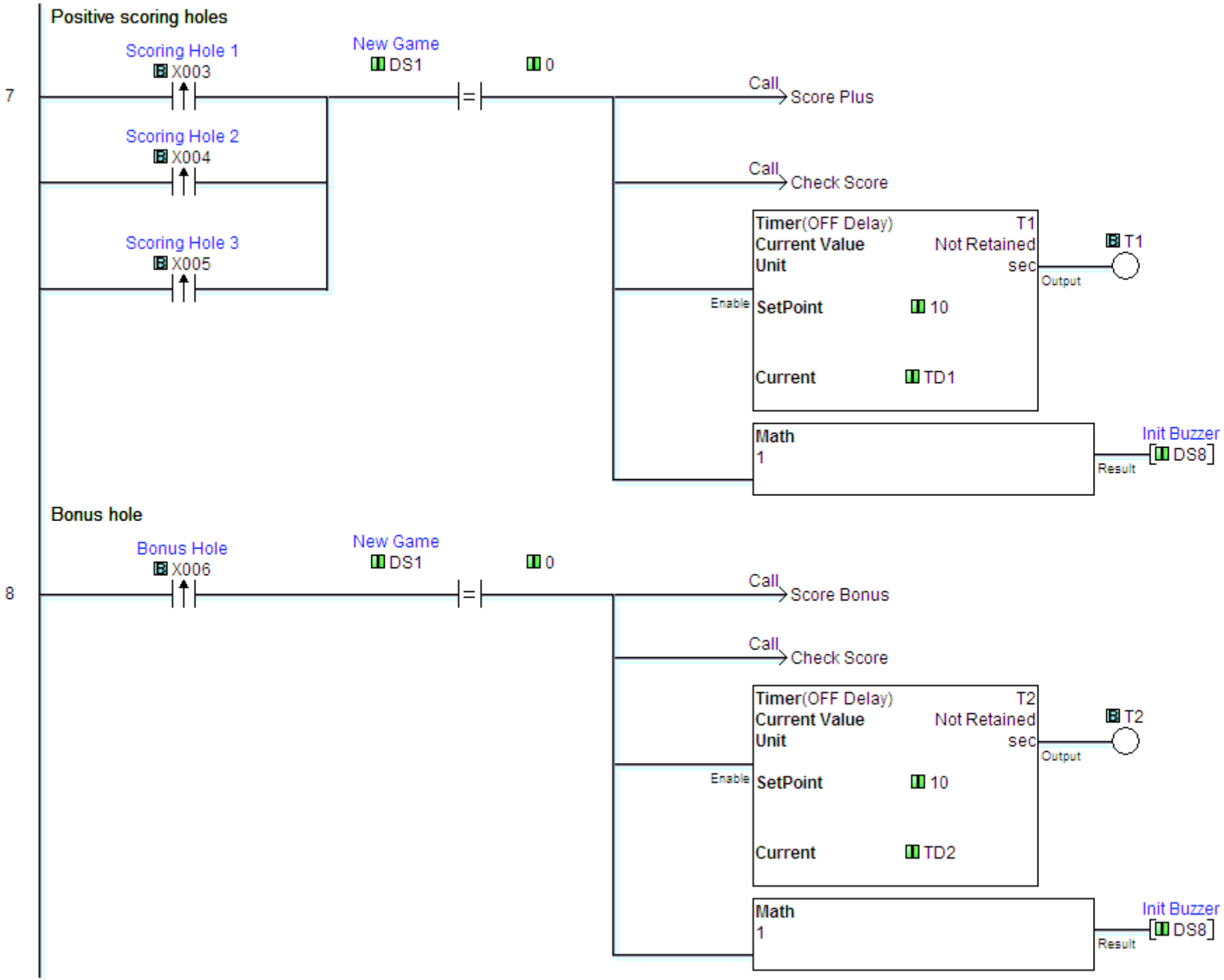
Reset button

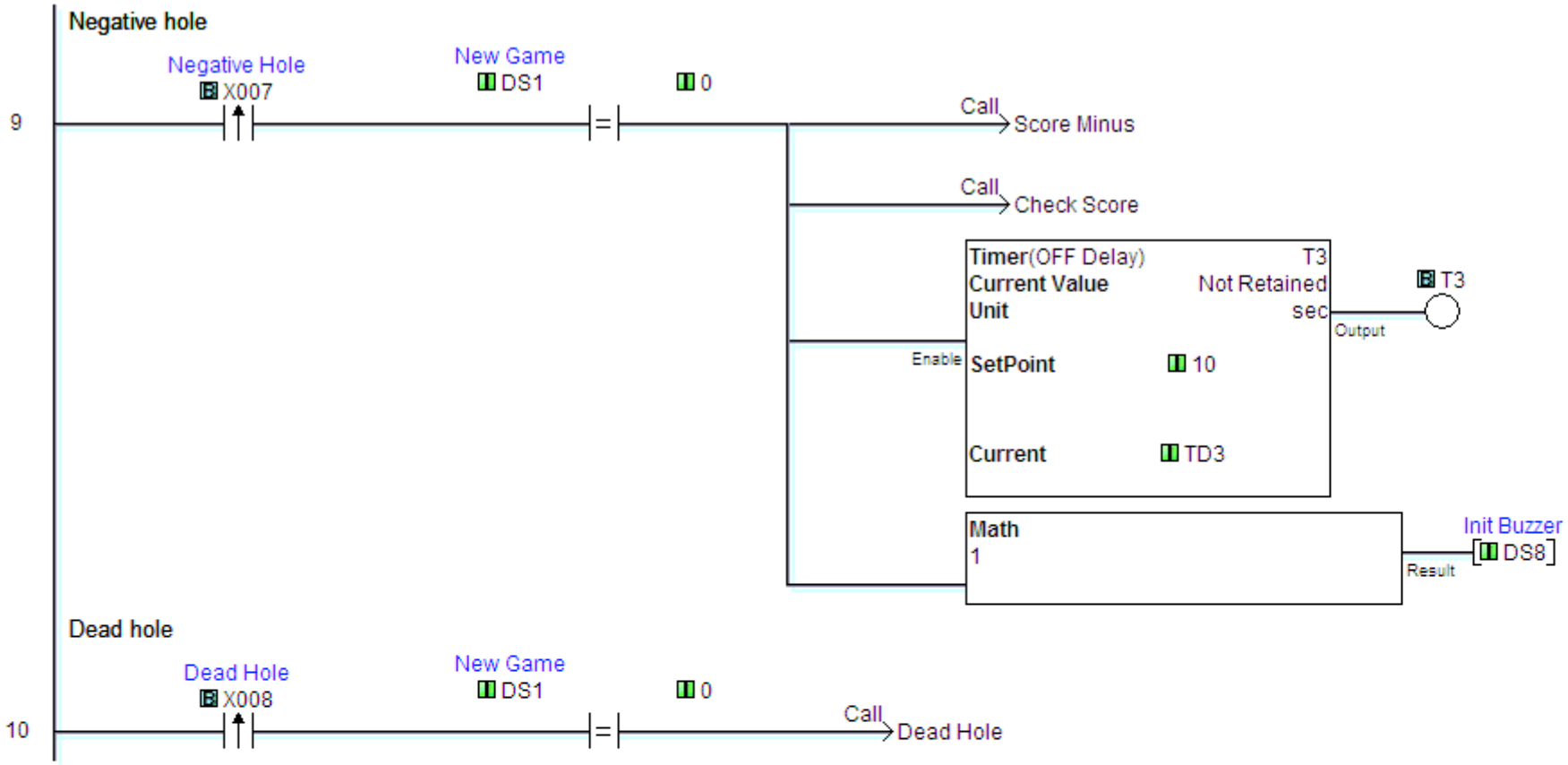
6

Reset Button
X001

Call Reset

Call Check Score


Positive scoring holes
7
Scoring Hole 1
X003
Scoring Hole 2
X004
Scoring Hole 3
X005
New Game
DS1
=
0
Call
Score Plus
Call
Check Score
Timer(OFF Delay)
T1
Current Value
Not Retained
Unit
sec
Output
T1
Enable
SetPoint
10
Current
TD1
Math
1
Init Buzzer
Result
DS8
Bonus hole
8
Bonus Hole
X006
New Game
DS1
=
0
Call
Score Bonus
Call
Check Score
Timer(OFF Delay)
T2
Current Value
Not Retained
Unit
sec
Output
T2
Enable
SetPoint
10
Current
TD2
Math
1
Init Buzzer
Result
DS8


Negative hole
Negative Hole
X007
New Game
DS1
0
9
Call
Score Minus
Call
Check Score
Timer(OFF Delay)
T3
Current Value
Not Retained
Unit
sec
T3
Output
Enable
SetPoint
10
Current
TD3
Math
1
Init Buzzer
DS8
Result
Dead hole
Dead Hole
X008
New Game
DS1
0
10
Call
Dead Hole

Game Over and light sequence when game over

11

Number Lives
DS2 = 0

Call Game Over

Score
DS3 ≧ 31

Math
1

Result → Init Buzzer DS8

Enable

Drum (TimeBase:ms)

Step	Duration	1	2	3	4	5
1	500	■	□	□	□	□
2	500	□	■	□	□	□
3	500	□	□	■	□	□
4	500	□	□	□	■	□
5	500	□	□	□	□	■
6	500	□	□	□	■	□
7	500	□	□	■	□	□
8	500	□	■	□	□	□
9	500	■	□	□	□	□
10	500	□	■	□	■	□
11	500	■	□	■	□	■
12	500	□	■	□	■	□
13	500	■	□	■	□	■
14	500	□	■	□	■	□
15	500	■	□	■	□	■

Output

1=Y001	5=Y005	9=	13=
2=Y002	6=	10=	14=
3=Y003	7=	11=	15=
4=Y004	8=	12=	16=

New Step

Current Step — Game Over Seq DS5

Elapsed Time — Game Over Seq Timer TD4

Complete → Game Over C1 C1

Reset Button X001

Reset

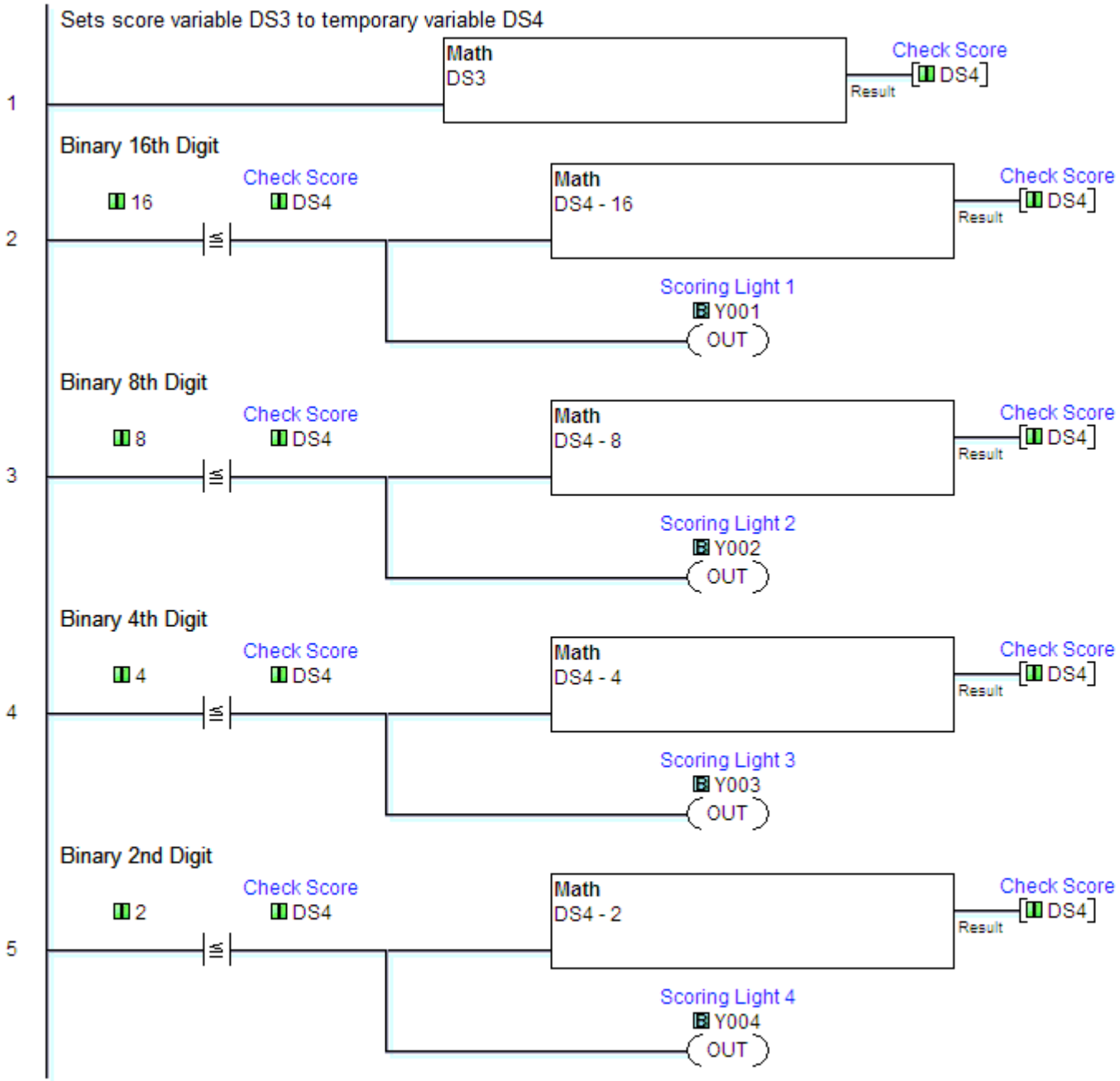
Displays score after game over light sequence ends

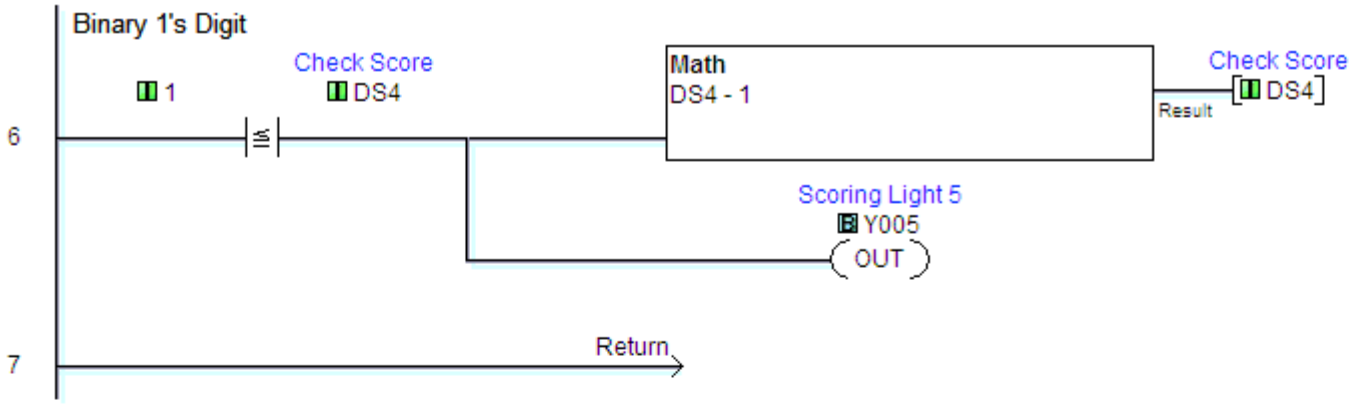
12

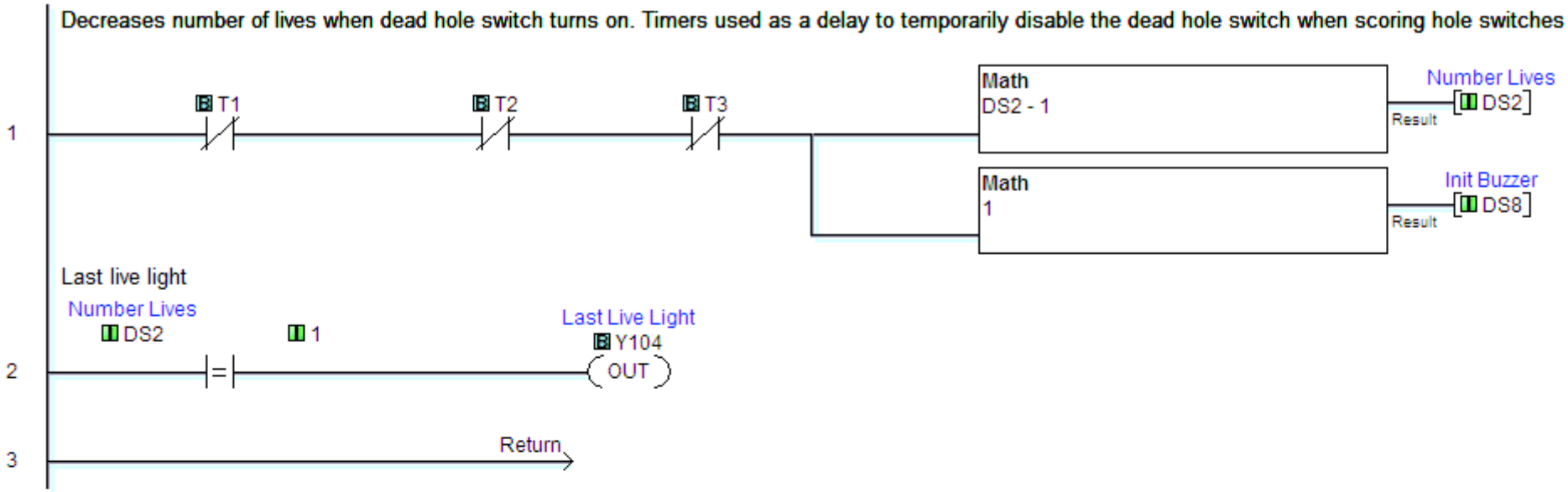
Game Over Seq
DS5 ≧ 15

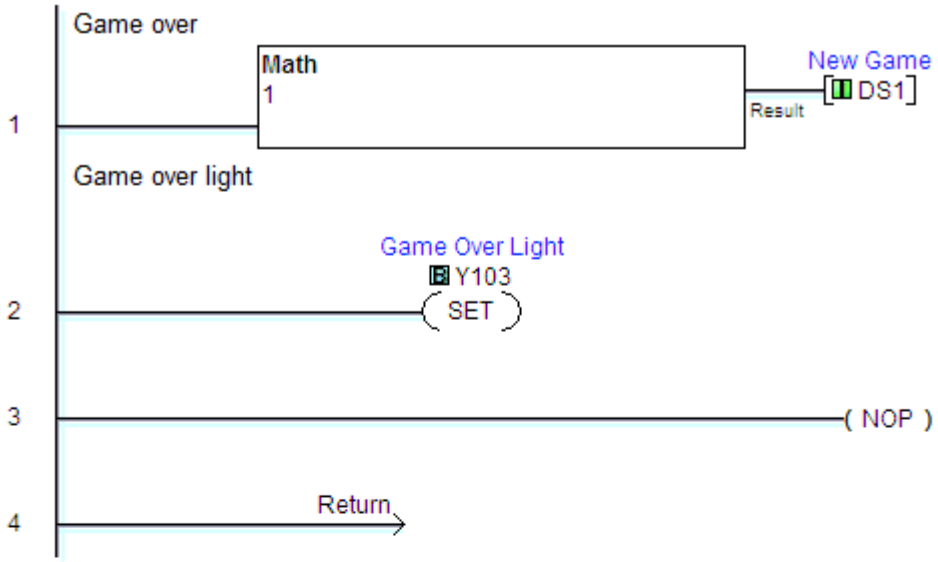
Call Check Score

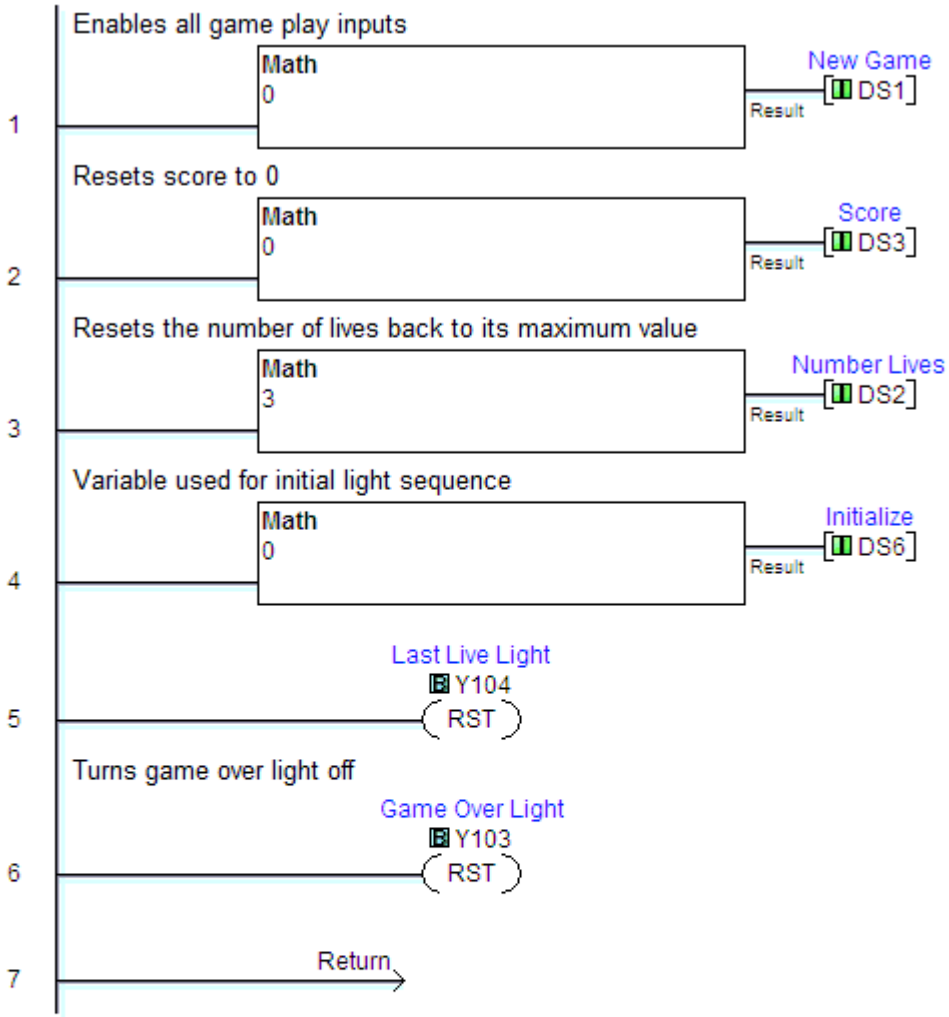

13
END

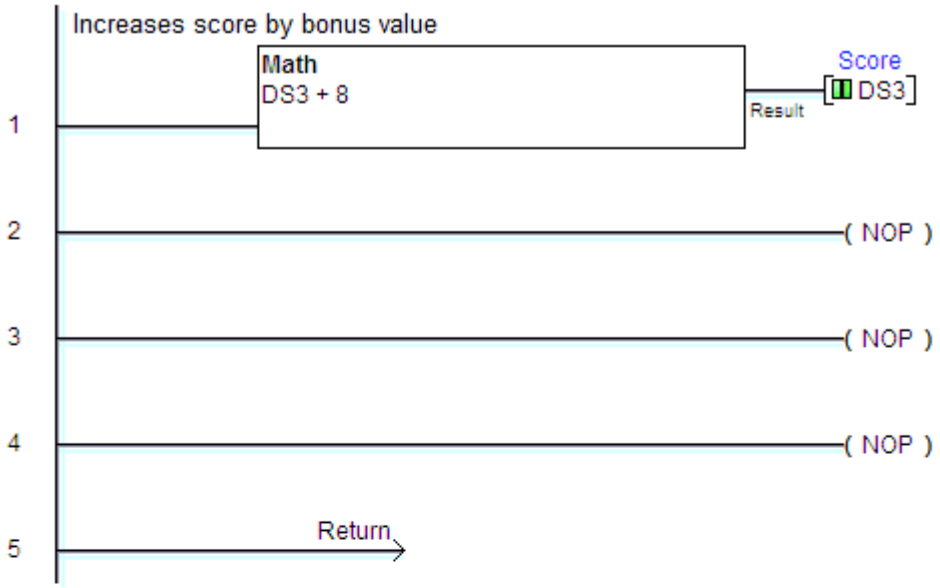

Sets score variable DS3 to temporary variable DS4
1
Math
DS3
Result
Check Score
DS4
Binary 16th Digit
2
16
Check Score
DS4
Math
DS4 - 16
Result
Check Score
DS4
Scoring Light 1
Y001
OUT
Binary 8th Digit
3
8
Check Score
DS4
Math
DS4 - 8
Result
Check Score
DS4
Scoring Light 2
Y002
OUT
Binary 4th Digit
4
4
Check Score
DS4
Math
DS4 - 4
Result
Check Score
DS4
Scoring Light 3
Y003
OUT
Binary 2nd Digit
5
2
Check Score
DS4
Math
DS4 - 2
Result
Check Score
DS4
Scoring Light 4
Y004
OUT

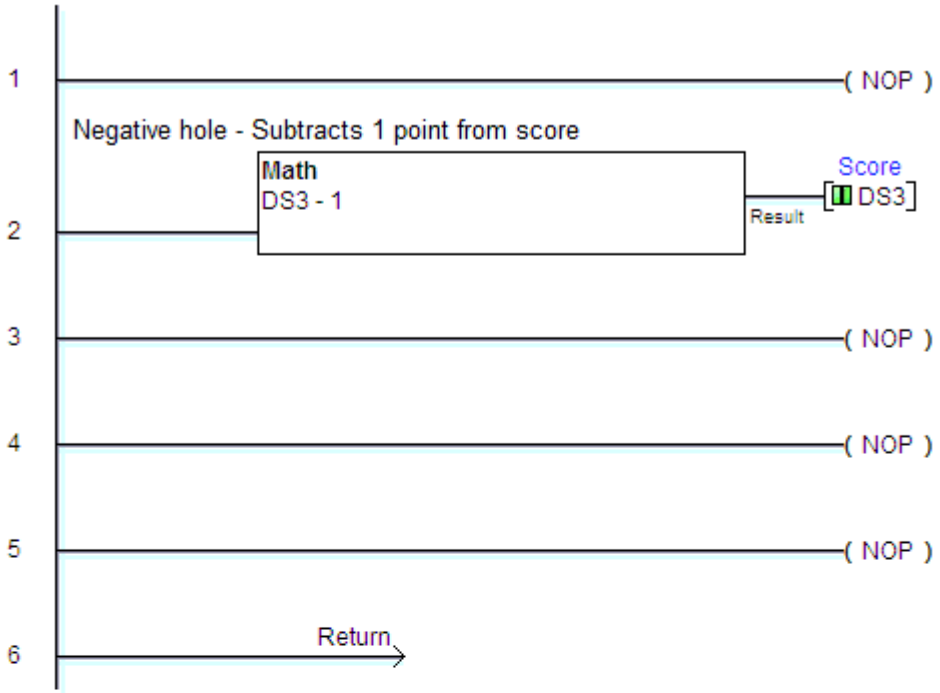

Binary 1's Digit
1
Check Score
DS4
Math
DS4 - 1
Result
Check Score
DS4
6
Scoring Light 5
Y005
OUT
7
Return

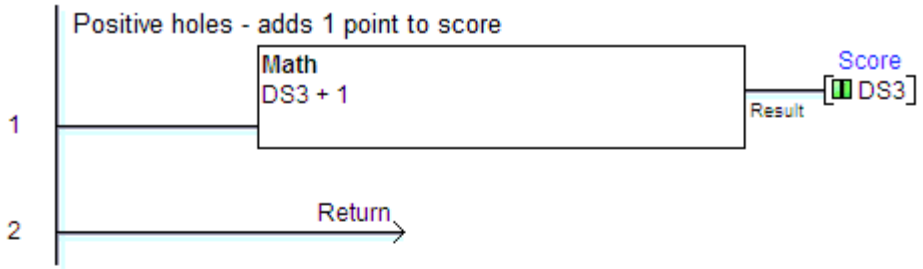

Decreases number of lives when dead hole switch turns on. Timers used as a delay to temporarily disable the dead hole switch when scoring hole switches turn on
1
T1
T2
T3
Math
DS2 - 1
Result
Number Lives
DS2
Math
1
Result
Init Buzzer
DS8
Last live light
Number Lives
DS2
1
=
Last Live Light
Y104
OUT
2
Return
3


Game over
Math
1
New Game
DS1
Result
1
Game over light
Game Over Light
Y103
SET
2
3
(NOP)
Return
4


Enables all game play inputs
Math
0
New Game
DS1
Result
1
Resets score to 0
Math
0
Score
DS3
Result
2
Resets the number of lives back to its maximum value
Math
3
Number Lives
DS2
Result
3
Variable used for initial light sequence
Math
0
Initialize
DS6
Result
4
Last Live Light
Y104
RST
5
Turns game over light off
Game Over Light
Y103
RST
6
Return
7


Increases score by bonus value
Math
DS3 + 8
Score
DS3
Result
1
2
(NOP)
3
(NOP)
4
(NOP)
Return
5


1
(NOP)
Negative hole - Subtracts 1 point from score
Math
DS3 - 1
Score
DS3
Result
2
3
(NOP)
4
(NOP)
5
(NOP)
Return
6


Positive holes - adds 1 point to score
Math
DS3 + 1
Result
Score
DS3
1
2
Return