Adaptive Electric Pen for Virtual Reality Rehabilitation

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Abstract— **In this FPGA implementation, we aim to create a virtual-reality rehabilitation environment of adaptive electric pen so that the patients can be trained for their hand movement. The infrared ray (IR) is used to sense the location of the electric pen in the maze. With 8-bits serial analog-to-digital converter, the received signal strength corresponding to the distance between the obstacle (pen) and the IR sensor is translated into digital signals for FPGA to further process. The maze is configurable and projected onto the screen by the FPGA output signal to the VGA port. The patients/players can see the maze on the screen and control the electric pen moving in front of the screen to experience the virtual reality. Even the maze on the screen is large, only three IR sensors having a spacing of 2 cm are used, which are mounted on a base carried by a track. The track is driven by a stepping motor, whose control signal is sent from FPGA so that the position of the electric pen can be traced and be kept in the detection region of three IR sensors. With these designs, we can avoid using a lot of IR sensors that are placed around the peripheral sides of the maze and can also reduce power consumption. Hence, the size of the maze can be varied from simple to complex training phases without altering the number of IR sensors. Also, the fatigue state of the patients due to repetition of the same action can be improved. With injection of entertainment elements, the rehabilitation can be more interesting.**

***Keywords*— Electric pen; Virtual reality; IR sensor; Kinect; Wii; Rehabilitation; FPGA**

I. Introduction

In the past, we usually use the real objects for doing rehabilitation or training, such as Aokana hand coordination assistive device (e.g. [1]). However, with only repetitive actions, the patients may suffer fatigue and resist rehabilitation. Hence, recently most of new training instruments or assistive devices introduce the ingredients of entertainment to encourage the patients. For example, Wii, Wii Fit [2] and the Kinect of Xbox [3] are all somatosensory devices that attract much attention. These devices have visual effect. The patients can see their scaled movement from the screen. However, sometimes the patients can not feel the reality in physical dimensions and thus the rehabilitation effects may be degraded. The technology of virtual reality may be used to improve this issue and to promote the rehabilitation.

In this implementation, we aim to create a virtual reality environment of the adaptive electric pen. The patients/players can control the electric pen moving in front of the screen by hands. The screen also shows the trajectory of the true movement of the electric pen in the maze without scaling. Hence, the patients/players can experience virtual reality. The mazes are designed for different training phase, from simple to complex, even with non-stationary objects so that the patients can be trained for precise hand control step by step. One timer counts the playing time of the electric-pen movement from the entrance to the exit in the maze. The displays of the maze, timer, and trajectory of the electric pen are all controlled by FPGA, outputted to the VGA port and projected onto the screen.

The IR sensor is used to detect the position of the electric pen. The distance between the obstacle and the IR sensor is measured by the IR reflected power. The analog voltage is converted to 8-bit digital representation by ADC0831 and then processed by FPGA. If only IR modules are used to sense the position of the electric pen traversing in the whole maze region, lots of IR sensors and ADC modules will be used, which is annoying for the power consumption and wiring. Thus, we propose to use moving IR sensors which track the position of the electric pen horizontally. Three IR sensors are adopted and mounted on a base. The spacing of two adjacent IR sensors is about 2 cm. The base is carried by a track, which is further driven by a stepping motor. When the electric pen moves to the right, the rightmost IR sensor will detect the reflected energy gradually. Thus, we send the command “Right Shift” to the stepping motor to move the base to the right so that the base can be kept to locate exactly below the electric pen to sense the height of the electric pen. Similarly, if the electric pen is shifted to the left, the stepping motor will drive the track to move the base to the left accordingly under the control of FPGA, as shown in Fig. 1. Thus, with this configuration, if the size of the screen is enlarged, only the length of the track needs to be increased and it is not necessary to change the number of IR sensors and ADC modules together with their controls.

We then use a projector to project the maze, position of the electric pen and the timer onto the screen from the back. The player/patient can stand in front of the screen with the electric pen in hand. The game has different levels. For example, a stroke patient can start from the simplest level to simply train the movement of his hand. Thereafter, a complex level can be used to train the meticulous control of the hand. Thus, rehabilitation can be accomplished in the game.

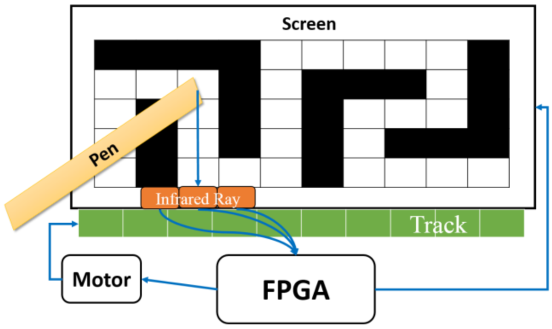

Fig. 1 Illustration of our implementation.

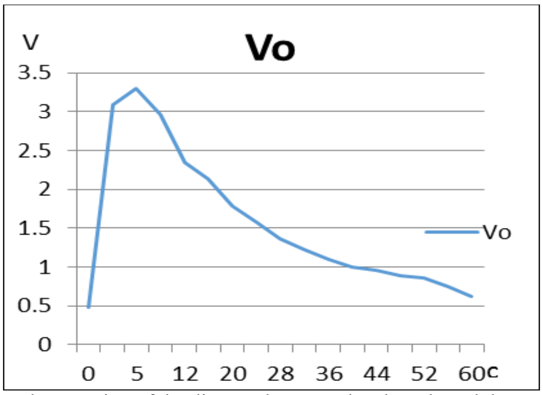

Fig. 2 The mapping of the distance between the obstacle and the IR sensor to the output voltage.

II. SYSTEM DESIGN

A. IR Sensors for Distance Measurement

The IR sensor can be used to measure the distance between the obstacle and the sensor by the reflected power. So in our implementation, it is adopted to detect vertical height of the electric pen. The output voltage related with the distance between the IR sensor and the obstacle is shown in Fig. 2. From 10cm to 60cm, we can obtain a curve that has exponential decay monotonically. The height of the maze is also restricted to this sensing distance.

However, for a fixed distance, the IR sensor does not always provide a constant voltage output. When the internal circuits are active, output voltage will rise from the normal value periodically as shown in Fig. 3. If all the voltage outputs are sampled and used, measured distance will vary frequently. For example, in case of 20-cm distance, the measured distance will become 10 cm during the period of the voltage deviation. Furthermore, background noise also exists. Therefore, in order to obtain a reliable measurement, we need to further process the digital data of the measured distance in FPGA to avoid the errors , which will be addressed in Sec. II.C.

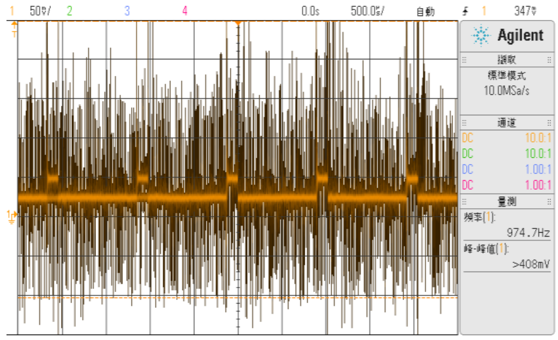

Fig. 3 Periodic output voltage deviation and noise.

B. 8-bits Serial A/D Converters

The IR sensor output is an analog signal. Hence, it is required to translate the analog signal to digital representation. We use an 8-bit serial A/D converter, which has sampling frequency around 10 KHz ~ 400 KHz [4]. The clock frequency of FPGA is around 58MHz. With a frequency divider, the A/D converter is driven by a clock of 57 KHz. After signal enters into the FPGA, we then transform the serial data from ADC into parallel 8-bit words. The scaling of the analog voltage to binary representation is given as below.

$$\text{Binary code} = \left(\frac{\text{Vin}}{\text{Vref}}\right) * 255 \qquad (1)$$

where Vin is the sensor output voltage and Vref is 3V reference voltage.

The serial-to-parallel conversion needs to coordinate with the low-active chip select (CS) signal. When CS signal is low, A/D converter samples and can translate the analog voltage into one 8-bit serial output. When CS signal is high, A/D converter stops translating. The FPGA collects the 8-bit serial input from the A/D converter and then generates an 8-bit parallel data when CS signal is high.

C. Signal Processing

To eliminate the measurement error due to the periodic voltage deviation of the IR sensors as shown in Fig. 4, we need to further process the digital data obtained from the IR sensors and A/D converters. Because the wrong voltage deviation is always higher than the correct value and environment noise also disturbs the measurement, we then propose to use the strategy of maximizing the minimum among the measurement. Adjacent 8 measurements are stored in the registers and form a group. The minimum among these eight samples in a group is first searched to avoid the periodic voltage deviation. However, if only the minimum is selected, we may encounter the condition of choosing the sample that is heavily disturbed by the noise, which is also undesired. Therefore, the maximum among the minimums of the eight groups is chosen to suppress the influence of the noise. With this strategy, the measurement variation can be greatly reduced.

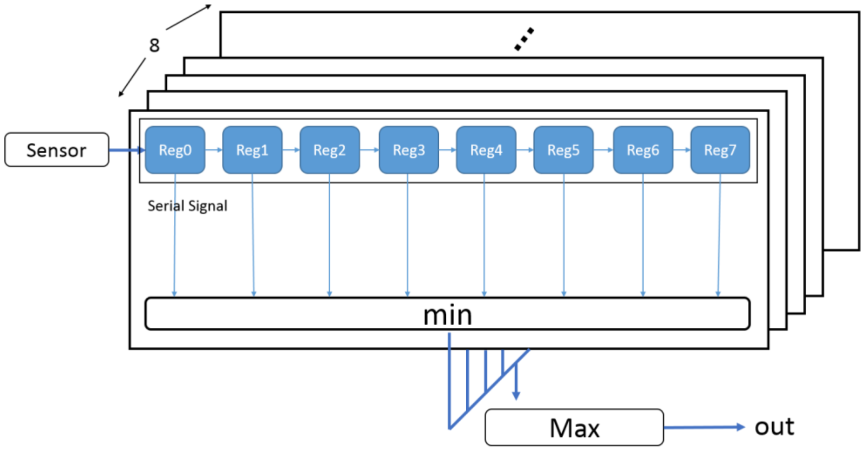

Fig. 4 Block diagram of the design that finds the maximum among eight group-minimums to mitigate the periodic voltage deviation of the IR sensor.

D. *Tracing the movement of electric pen*

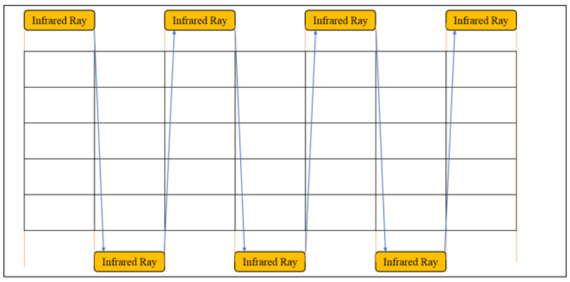

Fig. 5 Configuration of static IR sensor array.

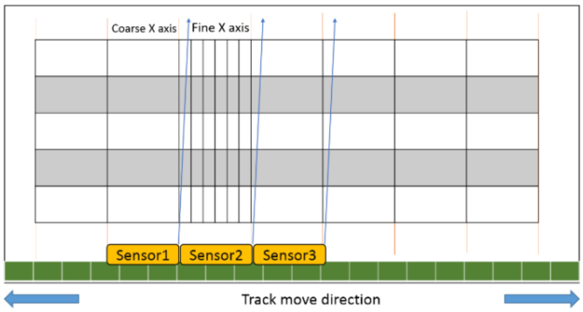

Fig. 6 Configuration of movable IR sensors.

To trace the movement in the maze, we not only need to detect the height of the electric pen, but also need to determine the horizontal position. An important issue then arises. How should we set up the sensors to sense the electric pen traversing in the whole maze? The straightforward solution may be to construct a sensor array around the upper side and the lower side of the maze. The IR sensor can be staggered to ensure balanced coverage of the upper and lower plane, as shown in Fig. 5. Hence, each square in the plane can be distinguished by different sensors together with the measured distance of that sensor. It can be expected that the response time of this arrangement is short. However, it has some drawbacks. First, if the size of the maze is changed, we need to change the deployment of the sensor array again. Meanwhile the hardware design in FPGA needs revisions, too. Besides, every A/D converter accompanies one IR sensor, the power consumption is large and wiring can be annoying. The requirements of registers for searching the maximum among the minimum to avoid the instable measurement is also increased.

To conquer the problem, movable IR sensors are designed. A stepping motor is utilized with gears and the track. Three IR sensors are mounted on the base. A control command can then be issued to the stepping motor to move the base of the IR sensors, as shown in Fig. 6. With such a configuration, this system has the following the advantages. First, only three IR sensors are used. The power consumption, register requirements, complicated wiring can be reduced. Second, if the size of the maze is changed, we only need to increase/decrease the length of the track. As to the hardware design in FPGA, revisions are not necessary.

TABLE. 1 COST OF TWO CONFIGURATION

Map Size = 5*10	Static IR sensor array	Movable IR sensor
No. of IR sensors	10	3
No. of A/D converter	10	3
No. of Registers	160	48
Response time	Short	Medium
Cost	High	Low
Analysis time	Long	Short
Flexibility	Low	High

Although we need to drive the stepping motor to move the base of the IR sensors following the horizontal movement of the electric pen and the response time is not as fast as that of the sensor array, it is still sufficient to be employed in this rehabilitation gaming system. The comparison of two configurations is given in Table I.

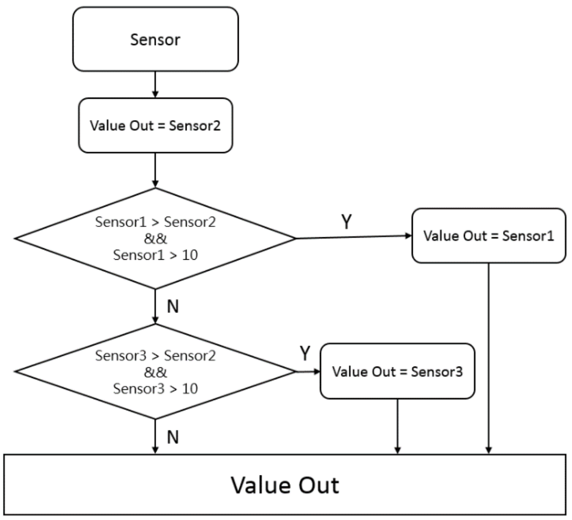

Fig. 7 Flow chart of height estimation of the electric pen.

The main functions of three IR sensors are different. The central sensor (sensor 2) is responsible for the height detection while the left and right sensors (sensor 1 and sensor 3) not only perform height detection but also determine if the electric pen has horizontal movement. When the output voltage of the central IR sensor is higher than the other two, the stepping motor stops and the distance measured by the central IR sensor is employed. If the electric pen shifts to the right or to the left so that the right or left IR sensor generates a higher output voltage than the other two, the stepping motor is activated to drive the track and the base following the movement of the electric pen until the central IR sensor is located below the electric pen. Meanwhile, the height estimated by the right or the left sensor that generates the higher output voltage is used. The flow chart is given in Fig. 7.

When the base of the IR sensors is moving, it may occur that the electric pen is not exactly above either one of three sensors even it is on top of the base. At this moment, the output voltages of three IR sensors all drop, which cause distortion in distance measurement. To solve this problem, first, we use 8 registers to store the 8 consecutive height estimations. The registers are driven by the original sampling frequency of 57 KHz. Thereafter, another 8 registers are adopted, driven by 220 Hz clock frequency that is close to the possible mobility of the electric pen. Each of the slowly-updated registers saves the maximum among the 8 quickly-updated registers. With this method, the estimated height of the electric pen can be frozen no matter the base or the electric pen is moving. If the electric pen keeps stationary, this method also works because the 8 quickly-updated registers and 8 slowly-updated registers all contain the same value. Its hardware design is shown in Fig. 8.

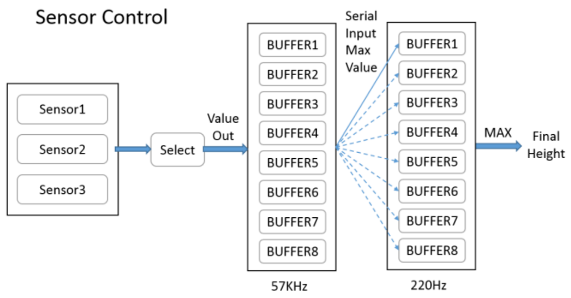

Fig. 8 Hardware design for freezing the height estimation during movement.

To obtain the correct horizontal position under the configuration of the movable sensors, the horizontal axis in the maze is partitioned into coarse grain and fine grain. When the stepping motor is driving the track and the base is moving, the value in terms of the fine grain is changed. If the increment or decrement in fine grain exceeds a threshold, then the horizontal position in terms of the coarse grain is updated.

E. Bump and Warning in the Maze

In order to inform the patients/players if their electric pen traverses along the correct path, we use different colors to indicate the state. In the safe state that the electric pen traverses within the allowable path, the position of the electric pen is indicated by the green square on the screen. If the electric pen is close to the wall (indicated by black squares), the position of the electric pen is shown by the yellow square as a warning state. In cases that the electric pen deviates from the allowable path, a red square is shown to remind the patients/players that a bump state occurs.

One square shown in the maze is divided into 9 sub-squares. Hence, the sub-squares in the traverse path adjacent to the wall are the warning region. When the position of the electric pen belongs to this region, we then use the warning state to remind the patients/players, but the game continues. If the electric pen enters into the wall zone, which is prohibitive to traverse, we will highlight the situation by the bump state. However, when the pen is near to the boundary of the wall, the display of the position of the pen may change rapidly between the yellow color and the red color. Thus, the patients/players feel uncomfortable. A hysteresis effect is then incorporated. When the electric pen is sensed to stay in the wall zone, a counter starts. If the counter output is greater than a pre-defined value, then the transition from the warning state to the bump state becomes valid. The patients/players can choose to restart from the entrance of the maze. Note that the counter to implement the hysteresis effect must be operated with a clock frequency faster than the mobility of the electric pens. Otherwise, the transitions can not be completed smoothly and recognized successfully.

F. Stepper Motor Control

The FPGA must send control signals to stepping motor so as to drive the base of the IR sensors moving to the right, to the left and stopping. The control signal to the stepping motor must be clearly identified without conflicts. Otherwise, the movement of the base oscillates and the power consumption is wasted. However, according to our driving strategy, the stepping motor will rotate counterclockwisely to move the base to the right when the output voltage of the right IR sensor is higher than the other two and the stepping motor will not stop until the central IR sensor generates higher voltage than the other two, which implies that the displacement of the base is sufficient and thus the movable sensor can catch up with the electric pen. Thus, we can avoidissuing the control signal to the right and to the left at the same time.

To generate counterclockwise (CCW) rotation and clockwise (CW) rotation, the control signal sent to the CCW or CW pins of the stepping motor contains a series of pulses with a certain frequency, as depicted in Fig. 9. When the base of the IR sensors does not need to move, we send a constant voltage to both CW and CCW pins.

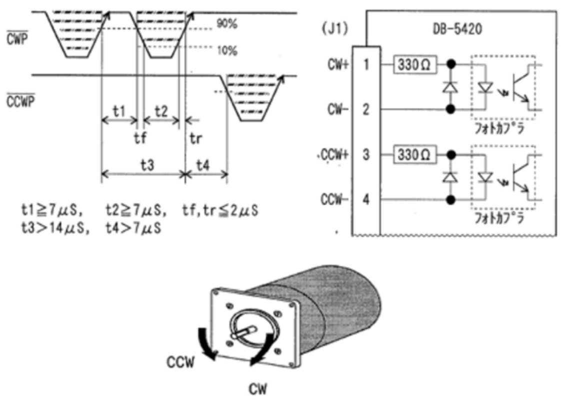

Fig. 9 Stepping motor control [5]

G. Display by VGA

The signal corresponding to the display of the maze is sent to the VGA port on the board from FPGA. The game contains different levels from simple to complex. To make the displayed image easily configurable, the components are all modularized, including the black rectangle for the wall and white rectangle for the traverse path. Furthermore, movable objects are also inserted to enhance the diversity and complexity of the game. The display of the timer is constituted by two seven-segment modules. The screen resolution is 800×600. The modules and objects to construct the maze are specified by the coordinates of two vertices of the diagonal, as shown in Fig. 10.

We then project the image onto the screen by the projector. The patients/players stand in front of the screen, use the electric pen to pass the maze. The position of the electric pen is calculated by FPGA according to the estimated height of the IR sensor and the movement of the stepping motor, and then a square is inserted into the displayed image to indicate the position of the electric pen. In addition, the color will be changed according to the safe, warning, and bump states. As shown in Fig. 11, all the modules and objects are integrated by the "OR" operations to the R/G/B pin with respective color settings.

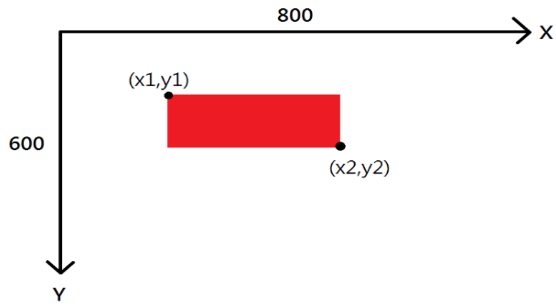

Fig. 10 Object and module design for display by VGA.

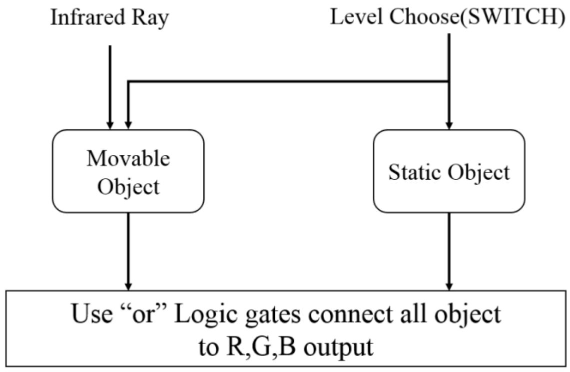

Fig. 11 Operations for integration of the modularized objects for display.

III. EXPERIMENT RESULTS

Finally, all the blocks are integrated to complete the adaptive electric pen for virtual reality rehabilitation. It contains different levels as shown in Fig. 12 for the simple level and in Fig. 13 for the middle level. The IR sensors, and the track carrying the base are also shown. We can see that the square pointed by the electric pen marks the position of the pen in the maze. Because the electric pen is in the traverse path, the blue color of the square shows that it is in safe state. The exit of the maze is marked by the green square.

Fig. 14 shows that the electric pen enters into the wall area and thus a red square is used to represent the bump state of the pen. In Fig. 15, the electric pen is close to the wall and thus is in the warning state. A yellow square is used to indicate the alert. Fig. 16 shows that the electric pen arrives at the exit of the maze.

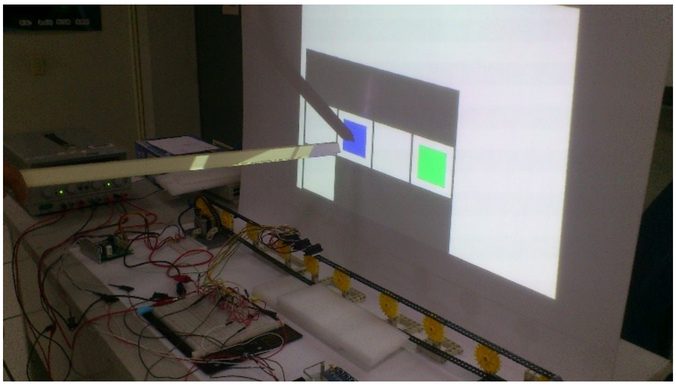

Fig. 12 A Simple level.

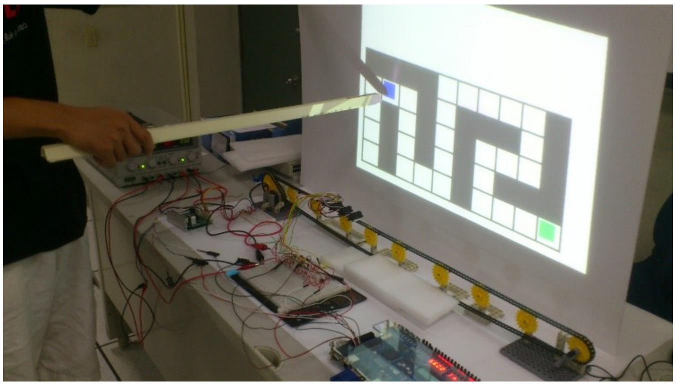

Fig. 13 A middle level.

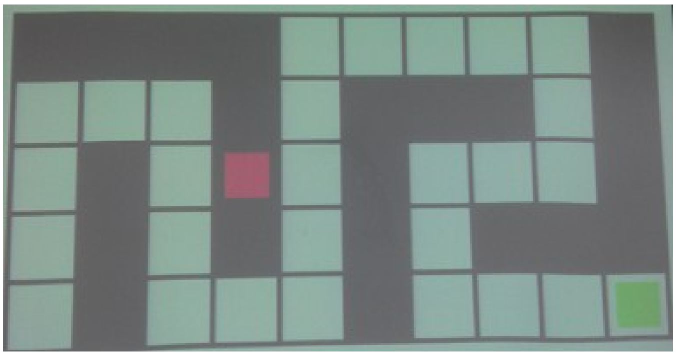

Fig. 14 A red square shows the bump state in the wall zone.

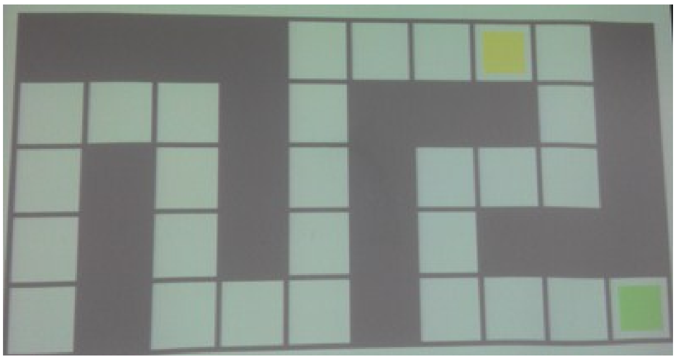

Fig. 15 Yellow square shows the warning state.

IV. DISCUSSION AND CONCLUSION

This implementation is developed for virtual reality rehabilitation using the adaptive electric pen. The design considers flexibility and diversity. For example, for the stroke patients, a simple maze with a large spacing can be used. For patients who need further training for the meticulous control of the hand, the complex maze with a narrow grid or moving objects can be adopted. Also unlike the conventional assistive devices and the rehabilitation instruments, this implementation not only considers the functionality for rehabilitation but also the entertainment property, which make the rehabilitation more interesting. In addition, because the system is implemented by FPGA, we can change the image of the maze easily. If the screen size is to be changed intentionally, only the length of the track needs to be revised. No more IR sensor is required.

In Wii or Kinect, the display of player's movement is only a scaled distance. Although the player has visual feedback, he can not feel the true physical dimension. However, in this work, unlike Wii and Kinect, we create an environment that the patients/players can see his movement exactly and thus experience virtual reality training or rehabilitation.

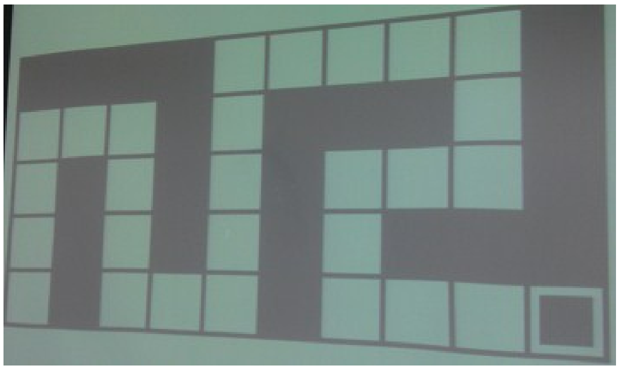

Fig. 16 Pass the maze. (black square)

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