Economical Design of a Magnetic Resonance Imaging (MRI) Quadrature Optical Encoder

Daniel Rajiv Jagessar[1], Kashu Yamazaki[2]
[1]*Department of Electrical Engineering, University of Arkansas, Fayetteville, AR 72701, USA*
[2]*Department of Mechanical Engineering, University of Arkansas, Fayetteville, AR 72701, USA*
(E-mail: drjagess@uark.edu)

Abstract -- A MRI compatible quadrature optical encoder is presented. MRI is a radiation free medical imaging technique that allows us to obtain decent contrast images of anatomical structures. An MRI scanner images water molecules in the body with a very strong magnetic field. Because of the presence of the strong magnetic field, use of any ferromagnetic or electrical components might harm human, hardware or both. To avoid any conductive materials or wiring inside the MRI room, custom-built fiber optic encoder is developed. In this paper, an MRI compatible quadrature encoder that could read the US Digital transmissive linear strip with LPI 127 will be discussed. The resulting encoder demonstrated the ability of producing the quadrature signal from the movement of a transmissive linear strip**.**

Keywords -- *Magnetic Resonance Imaging (MRI), Quadrature Optical Encoder, Signal Processing, Transmissive Linear Strips.*

I. INTRODUCTION

Magnetic resonance imaging (MRI) enables us to obtain a high-quality soft-tissue contrast that provides a means of noninvasive diagnosis for a human body and to avoid the administration of an additional radiation. The decent contrast images of anatomical structures are obtained by imaging the water molecules in the body with a very strong magnetic field. MRI scanners come in different field strengths, usually between 0.5 and 1.5 T [1]. Because of its imaging quality, MRI has been widely used in clinical environment not only for diagnosis but for surgical assistance. With a need for a real-time intervention along the ordinary diagnosis within a MRI scanner, robotic devices that can be operated inside the MRI room have been introduced. Because of the presence of the strong magnetic field, such mechatronic devices are limited to the use of non-ferromagnetic or non-electric components to protect both human and the hardware itself. Furthermore, the device is required not to cause any safety hazards or distort the results of the imaging process by creating additional magnetic fields or emitting radio frequency signals; and also the performance of the device should not be affected by the strong magnetic field of the MRI scanner.

Aside from the constraints in the large magnetic fields, the robots need to be small enough to operate within a small gap between the MRI scanner and the patient [2]. Along the robotic device itself, there must be a way to track the position, orientation and force being applied to the instrument in order to increase the precision of the operation and realize a feedback control of the device [3]. The sensing device should also obey the technical restriction imposed on the robotic device to be safely operated in the MRI scanner. Many times this tracking is done by some sort of optical system possibly including fiber optics [3][4].

This paper introduces the design and control of a low-cost MRI compatible quadrature encoder capable of reading US Digital transmissive linear strip.

II. PROBLEM STATEMENT

The objective of the project is to create a quadrature encoder that can read US Digital® transmissive linear strip or transmissive rotary encoder disk for a robotic device that will be operated inside the MRI scanner. In order to ensure the safety, no ferromagnetic or electric components can be present within a design that will be placed inside the MRI room. Also, it is preferred to be as small in dimension as possible.

III. MATERIALS AND METHODS

The presented quadrature encoder took the scheme of placing MR incompatible signal processors and other magnetic sensitive units outside the shielded room of the MRI. These controls were connected to the encoder module in the MRI scanner with fiber optic cables. Since fiber optics transfer data through light signals, high communication rates can be easily archived.

The custom-built encoder module was printed with Fused Deposition Modeling (FDM) 3D printer; hence, no ferromagnetic or electric components are present. A diagram of the entire encoding architecture is given in Fig. 1.

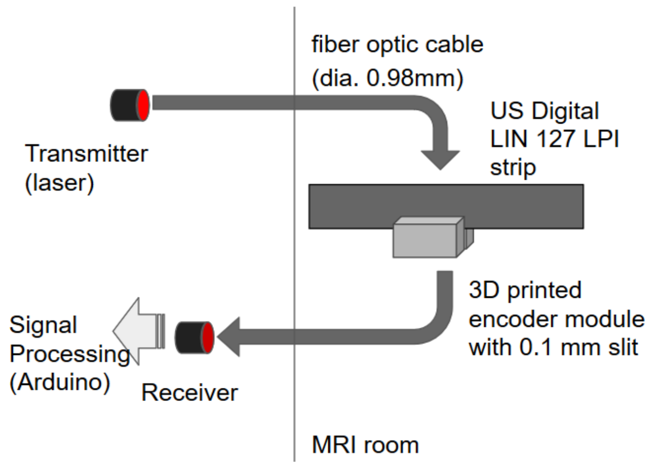

Fig. 1: A high-level diagram of the encoder, which consists of three major components: transmitter, encoder module, and receiver.

A. Transmitter Design

A laser (HiLetgo 650nm**)** was used as a light source for the transmitter. This laser provided sufficient light intensity so that the receiver can discern the opaque and transparent slots on the strip. In order to adjust the light intensity, a potentiometer was added to each laser. The circuit diagram is given in the Fig. 2.

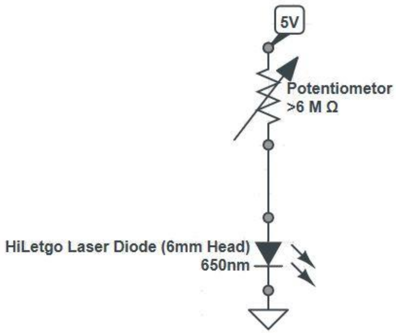

Fig. 2: A circuit diagram for the transmitter. Separate power sources were used for channel A and channel B.

B. Encoder Module Design

The custom-built encoder module, shown in Fig. 3, possesses the same working principles of a conventional quadrature encoder. The encoder module was aimed to read the US Digital transmissive linear strip (LPI 127). The strip has relatively high resolution considering the diameter of a fiber optic cable, which is 0.98 mm. Hence, it was imperative to receive light, not with entire cross-section, but with the limited region of the cross-section. An encoder module was designed and fabricated so that it allows the precise detection of the fine-tuned regions. The desired region was realized by adding a tiny slit on the encoder module as shown in Fig. 2. It turned out 0.1 mm width slit provides the reasonably accurate result from the iterative testing of a design.

To ensure that light traveled properly from the fiber optic cable on the transmitter side to the receiver side, the encoder module was printed as two separate pieces with both having an identical mounting hole, allowing them to be precisely aligned.

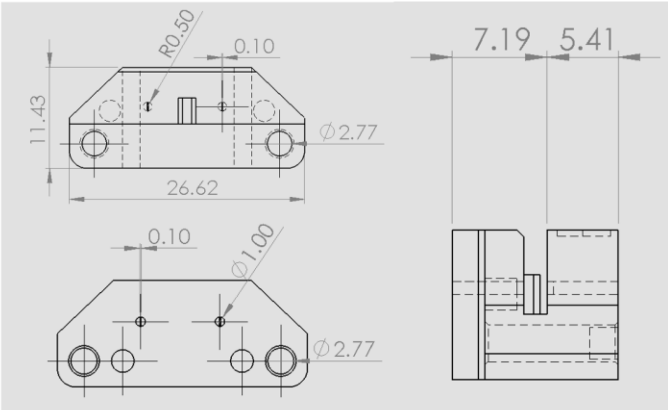

Fig. 3: A design of encoder module. Top-left: a transmitter side of the encoder module, which has a separation block between the two light source. Bottom-left: a receiver side of the encoder module. Right: the two modules are connected with the mounting hole.

C. Receiver Design

There are three main components in the receiver circuit: a NPN Phototransistor (IF D92), a NPN Transistor (2N3904) and a 2 - Input NAND CMOS Integrated Circuit (IC) Chip (4093). The Fig 4. shows the circuit diagram of the receiver. Note that DATA is the quadrature signal output from the receiver. The specification of the components are provided in Table II in Appendix.

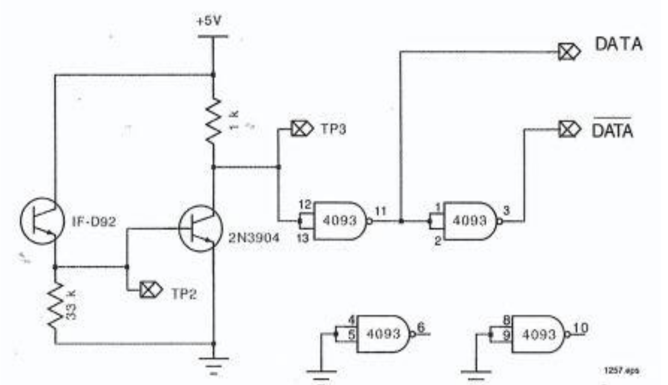

Fig. 4**:** A circuit diagram for the receiver, where DATA indicates the output of the encoder [7].

1) NPN Phototransistor (IF-D92)

The phototransistor was set up as a common collector amplifier. In this orientation, the phototransistor generates a response proportional to the light received until saturation takes place. Here, input signal is applied to the base terminal, and the output signal is taken from the emitter. Fig. 10 in Appendix shows the relation of response of the phototransistor and the wavelength. According to the figure, the laser used in the transmitter results in the 60% response of the phototransistor.

2) NPN Transistor (2N3904)

The 2N3904 is a common NPN bipolar junction transistor used for general-purpose low-power amplifying or switching applications. The transistor was configured to provide switching properties that allow current to flow to the IC Chip from the power supply according to the light received; when the light is present, lower voltage can be observed at TP3 and vise versa.

3) 2 - Input NAND CMOS IC Chip (4093)

The IC Chip uses the input voltage being received and converts this analog signal to a digital output. This IC chip was configured as an inverter in the circuit schematic because the voltage at TP3 is inversely proportional to the light received. The 4093 IC chip is designed with Schmitt Triggers. Schmitt Trigger devices are used to alleviate the issue that the output signal oscillates rapidly between HIGH and LOW. This is alleviation is done by the Schmitt Trigger hysteresis gap that extend the range of signal HIGH and LOW from average 40% - 50% to that of approximately 30% - 60%. These factors along with Table I: NAND Gate Output Logic enable to provide above 2.5V as a logic HIGH and below 0.75V as a logic LOW in 4093 IC chip.

TABLE I
NAND – GATE OUTPUT LOGIC

A	B	A NAND B
0	0	1
0	1	1
1	0	1
1	1	0

When not enough light is detected by the phototransistor, hence, when the collector gate of the phototransistor remained closed, current flows from the source to the IC chip. Because of the inverter configuration of the IC chip, the LOW signal is created. Similarly, when enough light is coming from the transmitter, which suggest a transparent region on a strip, the phototransistor became saturated and opens up the emitter, allowing a current to flow to the base of the transistor, and once the base is saturated, the collector gate is opened. This results in the current-flow from the emitter of the transistor to the ground. As a result, low voltage will be observed at input of the IC chip, creating the HIGH signal according to Table I. Therefore, the circuit can detect opaque and transparent regions respectively. The 33kΩ and 1kΩ resistors provides a DC path for leakage current and prevents overdraw of current when biasing to provide the appropriate voltage levels.

D. Signal Processing

The quadrature signals can be decoded to yield displacement and the direction of the movement as shown in Fig. 5. Pulses that appear on one of the two outputs correspond either to left or right transition (CW or CCW rotation). A decoding of the quadrature signals can provide three different resolutions: X1, X2, and X4 [5].

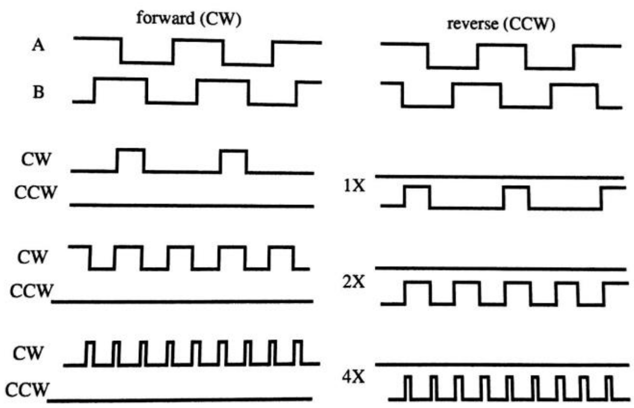

Fig. 5: Quadrature direction sensing and resolution enhancement [5].

Arduino UNO was used to decode the quadrature signals with the interrupt pins and ISR handler. Throughout the experiment, X1 resolution decoding was used.

E. Testing Setup

The two pieces of the encoder module was mounted together using plastic screws with the sliding frame mechanism that allows the uniform traveling of the strip for testing. Then the fiber optic cables were arranged to connect the transmitter, encoder module, and receiver as shown in Fig. 6. Emphasis must be made on the importance of sliding frame keeping the optical strip perpendicular to encoder the module as well as mitigating external errors of noises resulting in unsteady movements or shaking of the hand while sliding the strip. DATA pin was connected to the oscilloscope and Arduino interrupt pin to examine the behavior of the encoder. Two separate power supply were used for the transmitter to allow precise control of the light intensity. 3D printed 1 mm strip and the US Digital transmissive linear LPI 127 strip were used to measure the encoding quality of the encoder.

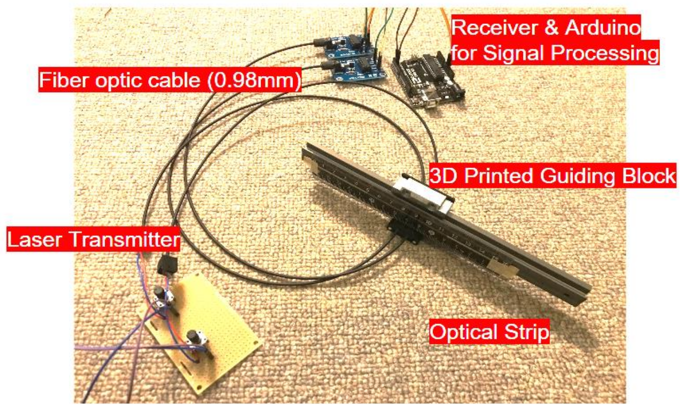

Fig. 6: Completed experimental setup of the encoder. Separate power supplies are attached to each of the laser transmitter.

IV. RESULTS AND DISCUSSION

We now show some experimental results obtained with the two types of the strips. Fig. 7 shows the result obtained with 3D printed 1 mm strip.

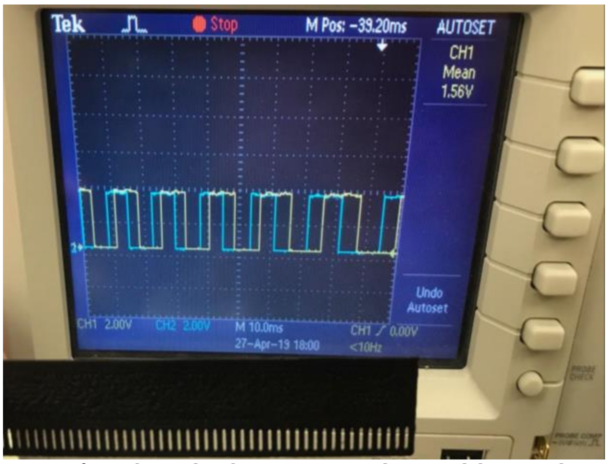

Fig 7 : Waveform obtained with 1mm 3D printed strip and the printed strip (black).

It was observed that the encoder detected LOW when the opaque region of the strip was in front of the slit on on the encoder module and vice versa for the transparent region. We can observe the clear quadrature signal as a result of a movement of the strip.

Fig. 8 shows the result obtained with US Digital transmissive linear LPI 127 strip. The relatively high-resolution strip was more sensitive to the light intensity that the transmitter provides, and the adjustment of the light intensity was needed. The careful polish of the ends of the fiber optic cable provided a better result.

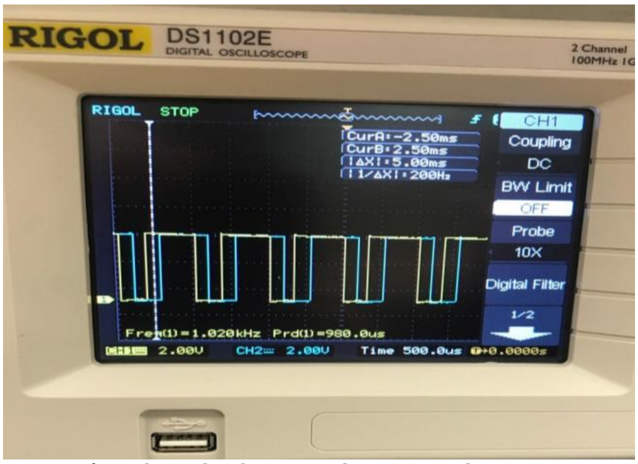

Fig 8: Waveform obtained with US Digital transmissive linear LPI 127 strip.

Further investigation was done on the resulting wave obtained with US Digital transmissive linear LPI 127 strip. The obtained wave of voltage transition was plotted in Fig. 9. As the figure reveals, two signals are not perfectly ¼ cycle out of phase with each other. This imperfect offset is thought to be due to the manufacturing error of the encoder module. This error can be potentially reduced by using a fiber optic cable with LC duplex connector, since the two outlets are separated by 6.25 mm where the desired offset is multiple of 0.05 mm for a LPI 127 strip. Also, wavelength of the transmitter can be adjusted so that the phototransistor in the receiver has better % response.

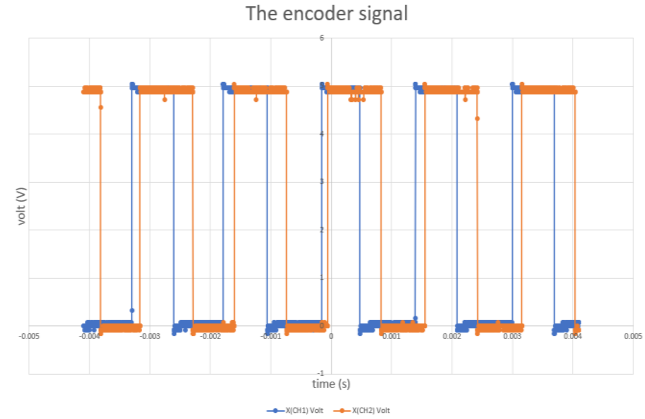

Fig 9: Voltage transition in signal A and B over time obtained by oscilloscope with US Digital transmissive linear LPI 127 strip.

V. CONCLUSION

We presented a MRI compatible small quadrature encoder, which enables to track the position or orientation of a robotic device that aims for a real-time intervention along the ordinary diagnosis within a MRI scanner. Yet, there are still some room for an improvement, the quadrature encoder demonstrated the ability of producing the quadrature signal from the movement of the US Digital transmissive linear strip. The primary contribution of this paper is to show that the simple setup of fiber optic cable and circuits can provide a means of sensing of a movement inside the MRI scanner.

APPENDIX

TABLE II
RECEIVER CIRCUIT COMPONENTS SPECIFICATIONS [6]

NPN Phototransistor (IF D92):	Optical Response: 700nm to 1100nm Data Rates: up to 25 kbps Bandwidth: x >= 15kHz Operating Temperature: - 40^0 C to 85^0 Collector Emitter Voltage: 30 V Emitter Collector Voltage: 5V Collector Peak Current: 100 mA
NPN Transistor Amplifier (2N 3904):	Frequency: x <= 100MHz Operating Temperature: -50^0C to 150^0C Collector Emitter Saturation Voltage: x < 300 mV @ I_c = 10mA. Continuous Collector Current: 200mA Collector Emitter Voltage: 40V
L 4093 Integrated Circuit Chip:	C Supply Voltage: -0.5 to 18V Input Voltage: -0.5V to 0.5V Operating Temperature: -65^0C to 150^0C

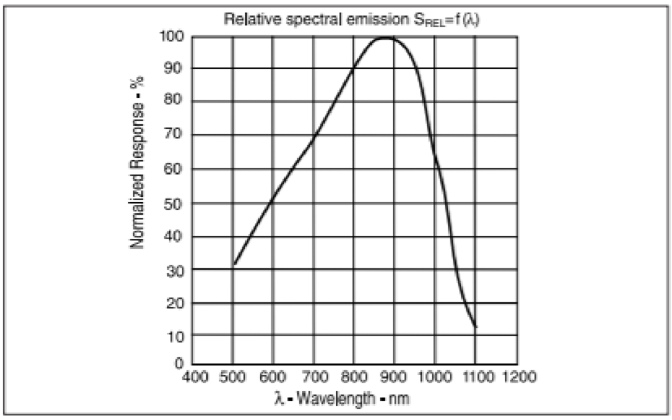

Fig 10: Typical detector response of IF-D92 versus wavelengths [6].

ACKNOWLEDGEMENT

Authors acknowledges Dr. Yue Chen, Assistant Professor in Mechanical Engineering department at the University of Arkansas, for providing materials and helpful advice during the experiment.

REFERENCES

[1] Berger, Abi. "Magnetic resonance imaging." *BMJ (Clinical research ed.)* vol. 324,7328, 2002.

[2] Gassert, Roger; Roland Moser; Etienne Burdet; Hannes Bleuler"MRI/fMRI-Compatible RoboticSystem With Force Feedback for Interaction With Human Motion". *IEEE/ASME Transactions on Mechatronics*. pp. 216–224. 2006.

[3] Krieger A, Iordachita II, Guion P, Singh AK, Kaushal A, Ménard C, Pinto PA, Camphausen K, Fichtinger G, Whitcomb LL "An MRI-compatible robotic system with hybrid tracking for MRI guidedprostate intervention". *IEEE Trans Biomed Eng*. 2011.

[4] Su, Hao; Michael Zervas; Gregory A. Cole; Cosme Furlong; Gregory S. Fisher "Real-time MRI-Guided Needle Placement Robot with Integrated Fiber Optic Force Sensing". *IEEE International Conference on Robotics and Automation* 2011.

[5] Alciatore, D. G., & Histand, M. B. "Introduction to Mechatronics and Measurement Systems." *New York,: McGraw- Hill*. (2011).

[6] ElectronixExpress,"Plastic Fiber Optic Phototransistor" *IF-D92 datasheet*

[7] Industrial Fiber Optics Inc, Educational Communication Kit: Radiant Energy in Action, *"A Hands-On Introduction to Fiber Optics Communications",* 2002.