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Design of a joint angle measurement system for the rotary joint of a robotic arm using an Incremental Rotary Encoder

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Abstract. The design of a prototype system that measures the joint angles of the rotary joint of a robotic exoskeleton is presented in this work. An incremental rotary encoder is a sensor that can be connected to any rotary joint to measure the angle of rotation, speed of rotation, direction of rotation (clockwise or counter-clockwise motion) as well as the acceleration of a joint. The measurement system using a rotary encoder which generates an electrical signal either analog or digital according to the rotation movement was designed in this work. A prototype rotary joint having a 270° range of motion was fabricated with ABS plastic using 3D printing and then connected to an incremental rotary encoder to measure its speed and angle of motion. A robotic exoskeleton was then proposed to be used with the tested and developed measurement system.

1. Introduction

Robots and robotic devices with numerous functions are readily available to build and design using prototyping techniques and off-the-shelf components. Robots such as mobile robots, arm type robots, or humanoid robots have been extensively studied and available either as devices that can be purchased commercially or can be built from scratch. Mobile robots [1] make use of wheels, electromechanical drives and motors to move (either forward, backward, turn left or right) with or without a payload connected. Arm-type robots [2] are primarily designed to resemble and function in a manner similar to the shoulder and elbow joint of a human being. Arm-type robots are commonly used for reaching tasks and as a pick and place mechanism. An arm type robot may be connected to a mobile robotic base to further extend the extent of reach. An arm-type robot has to be connected at its end to a gripper so as to execute a pick and place operation after reaching a target location through the extension of its arm. Grippers function in a similar way as the human fingers and are used to grip objects firmly which can be transported to another location. Humanoid robots [3], as the name implies are in the shape and form of a human being. Humanoids execute locomotory motion [4] through the use of robotic legs or mobile robots; they execute reaching tasks through the integration of arm type robots and implement gripping tasks via the integration of robotic grippers [5].

The mechanism through which a robot is able to perform movement is through the integration of pneumatic [6], hydraulic [7], electromechanical [8] drives such as motor, although there exist an area of research in robotics that makes use of soft materials and mechanisms for movements [9,10]. Pneumatic drives make use of compressed air using a compressor or piston-cylinder arrangement. Hydraulic drives utilize fluids for power transmission to piston for linear or prismatic motions.



Pneumatic and hydraulic systems possess advantage of high power over weight ratio although setup can be bulky. The more popular electromechanical drives make use of motors such as Direct Current (DC) motors, stepper motors or servomotors. While DC motors [11] have higher speed, compact and easily integrated for any robotic application, they have lower torques and would require the integration of optical encoders in order to measure the speed and angle of motion. DC motors use gear reduction systems to reduce the speed of rotation and improve torque characteristics. These characteristics make them suitable for use in mobile robots. Stepper motors [12], on the other hand experience higher torque, slower speed, the rotational speed of motion is proportional to the frequency of input pulses and can therefore be controlled using open loop controllers or microcontroller circuit. Servo motors [13] allow for a more precise control of rotary speed and angle and are suitable for use in open loop as well as closed loop controller applications.

Irrespective of the drive system used to actuate a robot for a specific task, there is the need to accurately measure the angle, speed and acceleration of a joint [14] and in some cases, to have a 2 measurement system of the angle in order to ensure improved accuracy and precision of measurement results in case one measurement system fails in safety-critical applications. In this work, an angle and speed measurement system using an incremental rotary encoder connected to a prototype robotic joint was designed, developed and tested.



Figure 1. The LPD3806 600BM G5 24C Rotary Encoder

The encoder (i.e. rotary encoder as shown in Figure 1, has many applications such as accustomed to determine rotational speed, $\dot{\theta}$, angle, θ , and acceleration, $\ddot{\theta}$, of an object, accurately measure the rotation of a joint or motor and provide direct physical response of motor position or joint position as well as speed of rotation. Dissimilar to potentiometers, they can rotate indefinitely about the axis of motion perpetually. Rotary encoders are designed with diverse kinds of resolutions in which the quantity of pulses or steps produced for one full rotation varies from 16 (2^4) - 1024 (2^{10}) pulses/revolution.

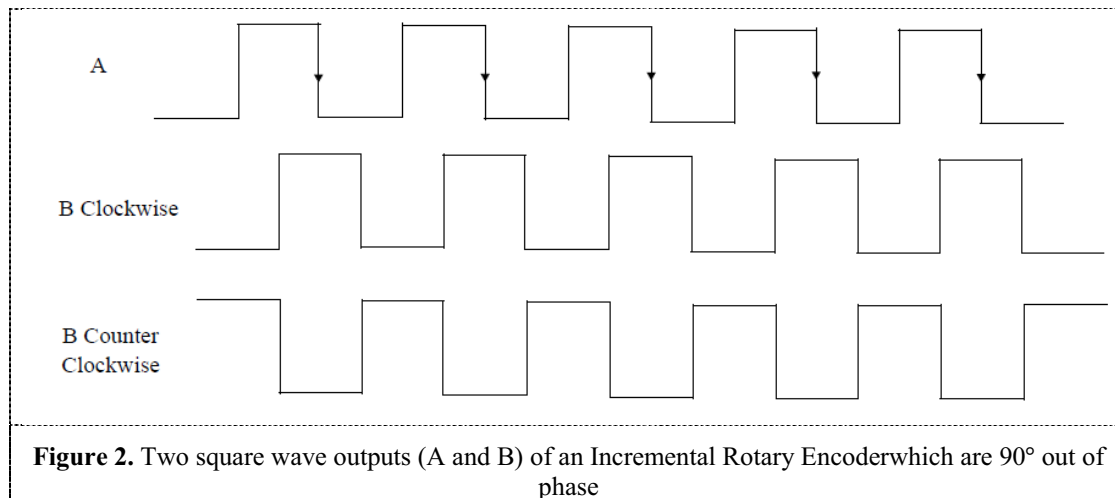


Figure 2. Two square wave outputs (A and B) of an Incremental Rotary Encoder which are 90° out of phase

As shown in Figure 2, a rotary encoder is designed with two square wave outputs (A and B) which are 90° out of phase with one another. Whenever the falling edge is a signal pulse, the value of the B signal pulse is taken. In Figure 2, the B signal wave is regularly positive when the encoder turns clockwise. B signal pulse becomes negative whenever the encoder is rotated counter-clockwise. With the aid of a microcontroller connected to both outputs, it becomes viable to figure out the direction of rotation. Also by counting the number of A-signal pulses, how far the encoder has turned or the angle of motion can be determined. The motion of the encoder disc as a quadrature modulated pulse train is represented by the two outputs (A and B). Furthermore, through the addition of a third index signal that pulses once for one complete revolution, the exact orientation indicating motor position or angle can be known.

2. Design of measurement system

The specifications, electrical connections and algorithm to measure the speed of a robot arm in revolutions per minute, direction and angle of a robotic joint using a LPD3806 600BM G5 24C incremental Rotary Encoder is presented in this section

2.1. Specifications:

The specifications of LPD3806 600BM G5 24C Rotary Encoder are thus:

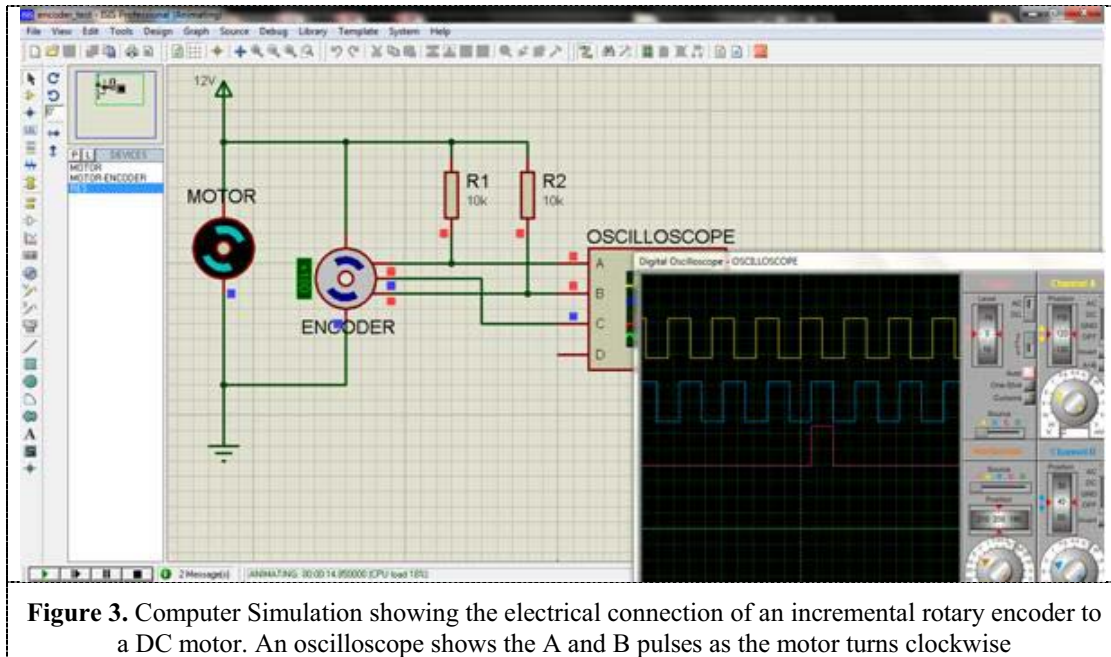
- Single phase is obtainable by 600 pulses per revolution, therefore, 2-phase output turns to 2400 ($600 \times 2^2 = 2400$) pulses/revolution
- Maximum mechanical speed of 5000 revolutions per minute
- Response frequency is within the range of 0 to 20KHz

2.2. Connections:

Table 1. Wiring Connections of an incremental rotary encoder.

Wire Colour	Representation
Red wire	DC Power input, (5-24V DC)
Black wire	DC Power input, Ground (0V)
Green wire	A-phase output
White wire	B-phase output

Electrical connection together with each wire representation for the LPD3806 600BM G5 24C Incremental Rotary Encoder is shown in Table 1. A pull-up resistor of $10\text{k}\Omega$ is connected to the A and B phase signal outputs of the rotary encoder because it is an open collector encoder. This is because without the pull-up resistors, the encoder will not function as desired. The A and B phase output wires must not be directly connected to the supply voltage, V_{cc} so as to prevent the output triode from getting damaged via burning. A computer simulation presented in Proteus ISIS of an incremental rotary encoder connected to a DC motor is in Figure 3.



2.3. Measuring RPM Using an encoder:

Revolutions per Minute, (also called RPM) indicate the speed at which a rotary joint turns and can be sensed using some large diversity of methods. The most frequent sensors used to measure RPM include optical encoders and Hall-effect sensors. These sensors generate one or more pulses per revolution (this depends on the particular sensor used). The RPM varies due to the differences in the waveforms generated. As RPM gets larger, the period (T) and pulse width (W) decreases.

For the incremental rotary encoder, both the period (T) and pulse width (W) are proportional to RPM. The frequency (or period) of either A or B signal provides a direct indication of the revolutions per minute or the speed at which the joint rotates. The angle of the robotic arm or motor position (θ) is derived by counting the number of pulses. The A-B phase is used to determine motor direction and position while the B signal pulse outputs a positive signal with a clockwise rotation. For counter-clockwise rotation, the B signal pulse outputs a negative signal.

2.4. Software Algorithm:

The flowchart for the angle and speed of a robotic arm is represented in Figure 4. The defined variables named “revolutions” and “encoder position” are defined. The angle of the joint or motor for the LPD3806 600BM G5 24C Incremental Rotary Encoder having 2400 pulses for one complete revolution is 360° , Hence, the angle is given thus:

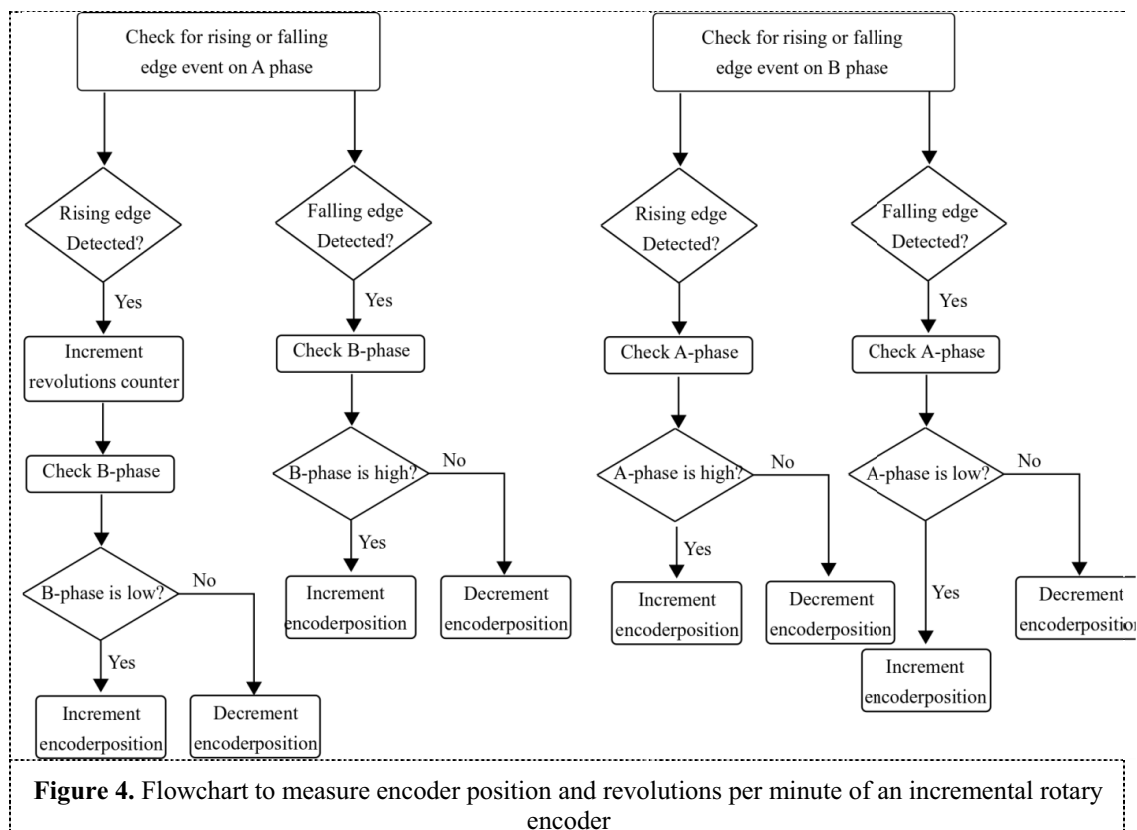
$$\text{Angle} = \text{encoder position} \times \frac{360}{2400}$$

$$\therefore \text{Angle} = \text{encoder position} \times 0.15$$

The software code returns the revolutions per second. Therefore, the revolutions per minute (rpm) is given by:

$$\text{revolutions} \times 60$$

The pulses keep counting up to $2^{16} = 65536$ after which there is a reset to zero. Therefore, the rearrangement of the pulse count to 0 after reaching 2400 is essential. For the designed robot arm, the joint would not make a full 360° rotation so that there is no requirement for a reset. More importantly, the direction of positive rotation is essential to note in the installation of an incremental rotary encoder. The pulse counter variable will count down from 65536 to 0 instead of count up from 0 to 65536 if the encoder is installed in such a way that its rotation is in the counter clockwise position..



3. Design of a Rotary Robotic Joint

The sequence for fabricating the rotary robotic joint that will form part of the robotic exoskeleton using 3D printing (rapid prototyping) is by the following processes:

- CAD Design of parts using a 3D Modeling CAD software such as AutoCAD, Sketchup or SolidWorks®;
- Conversion of CAD design to *.stl* format;
- Conversion of the *.stl* file into g-code using a slicer software;
- Transfer of file to 3D printer machine via a wireless network, USB or MicroSD card;
- Loading plastic filament and printer setup;
- Layer by layer building of the mould part (printing) via heated plastic extrusion from the nozzles;

- Removal of part from the 3D printer;
- Post processing of the printed part (involving removal of support material); and
- Using the printed part (application).

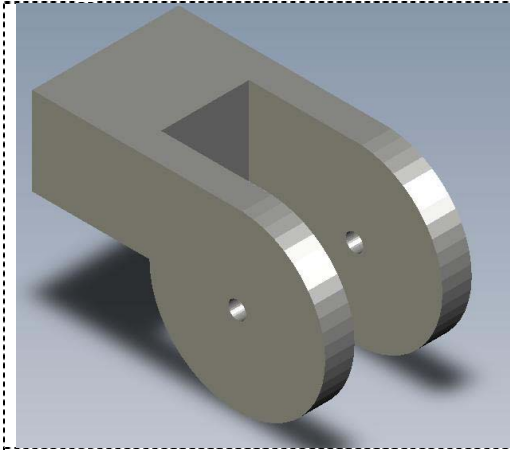


Figure 5a. The first part of the designed rotary joint in Solidworks®.

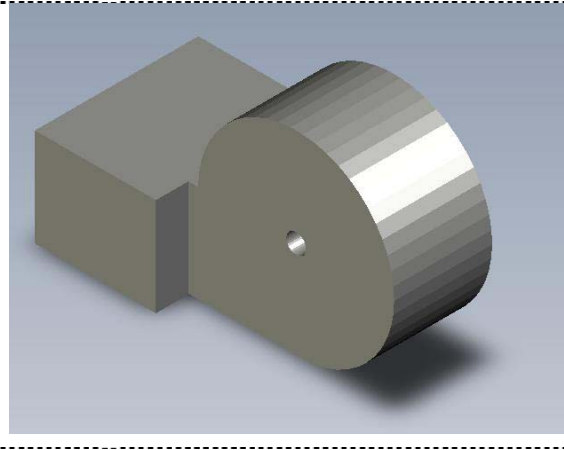


Figure 5b. The second part of the designed rotary joint in Solidworks®.

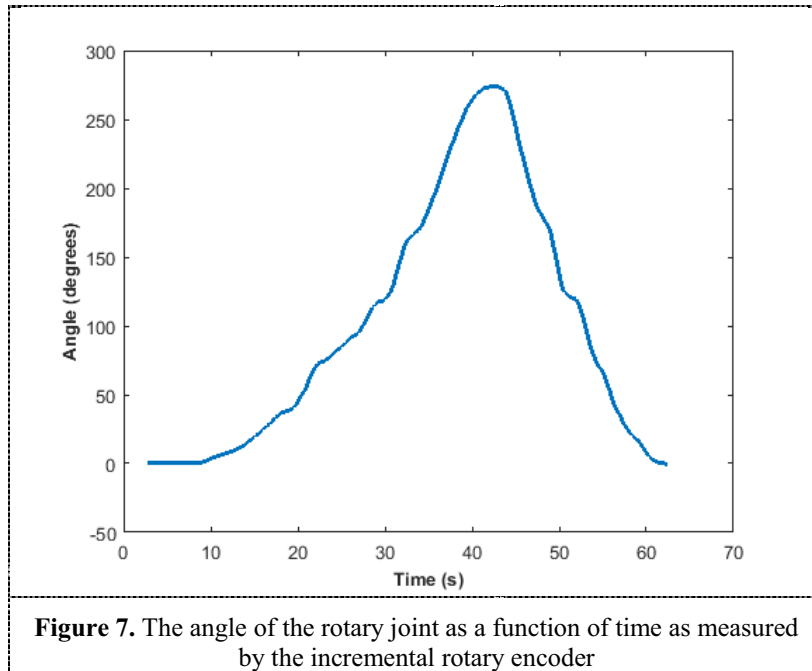
3D printing with Acrylonitrile Butadiene Styrene (ABS) plastic was used to produce the parts for the rotary robotic joint. A primary advantage of 3D printing is its ability to produce very complicated or intricate geometries with relative ease when compared to the other fabrication methods. Complex shapes such as a hollow structure can be designed through the introduction of another printer material to act as a supporting material, which can be easily dissolved away during the post processing of the part. PolyVinyl Alcohol (PVA) was used as a support structure because it is water-soluble and can be dissolved after the 3D printed structure has been soaked in water after a few hours (this depends on the density and location of the support material). The designed robotic joint showing the parts in SolidWorks® is shown in Figure 5a and b. The parts shown in Figure 5a and b are assembled as a hinge joint with the incremental rotary encoder connected as shown in Figure 6.



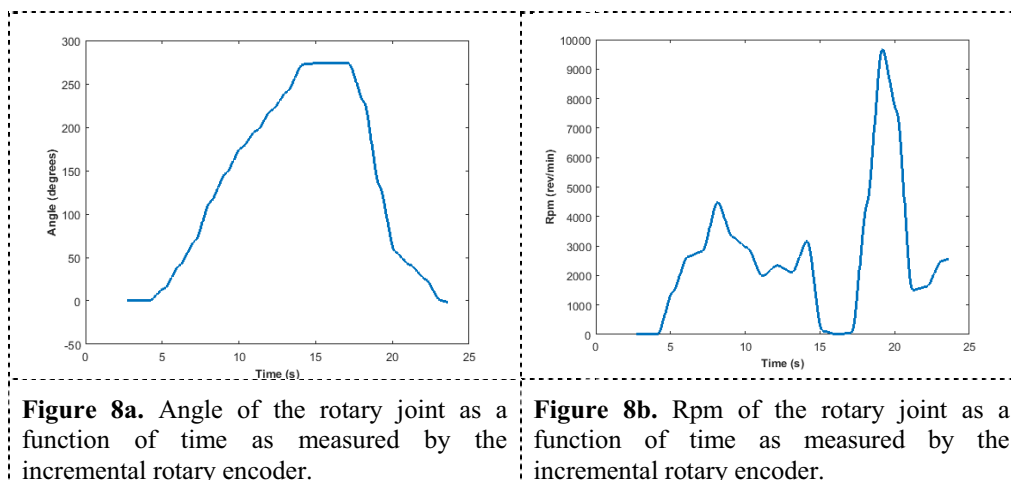
Figure 6. An incremental rotary encoder connected to a rotary joint

4. Results and Discussion

The graph of the angle of the prototype joint as it is being moved as a function of time shown in Figure 7. From the figure, it can be seen that the joint is rotated by a user through the joints' range of motion: from 0° to 270° and back to 0° . This shows that the rotary encoder is not only suitable for measuring the angle of motion, it can also be used to measure the direction of motion either clockwise or counter clockwise motion.



The graph of the angle as well as the rpm of the prototype joint as it is being move against time is shown in Figures 8a and b. The data plotted in figures 8a and b are recorded simultaneously. It can be seen that the rpm plot of Figure 8b provides information about the speed of the joint. If the joint moves very quickly, the rpm increases and as the joint comes to rest at any angular position, the rpm decreases down to zero. A maximum rpm of 10000 revolutions per minute was measured by the incremental rotary encoder. From both figures 8a and b, at the maximum angle of 270° , an rpm of 0 was recorded because the joint was not moving at that time.



The incremental rotary encoder is been tested to work with a 3D printed rotary joint. The application of this design can be implemented in a robotic exoskeleton (Figure 9). This exoskeleton is a passive robotic device, hence, an incremental rotary encoder will be easily integrated into it so as to measure and record the range of motion of the device as it is being used. In this way, a quantitative measurement regarding information relating to movement (such as angle, speed and direction) when the robotic exoskeleton is in operation can be determined via integration with an incremental rotary encoder.

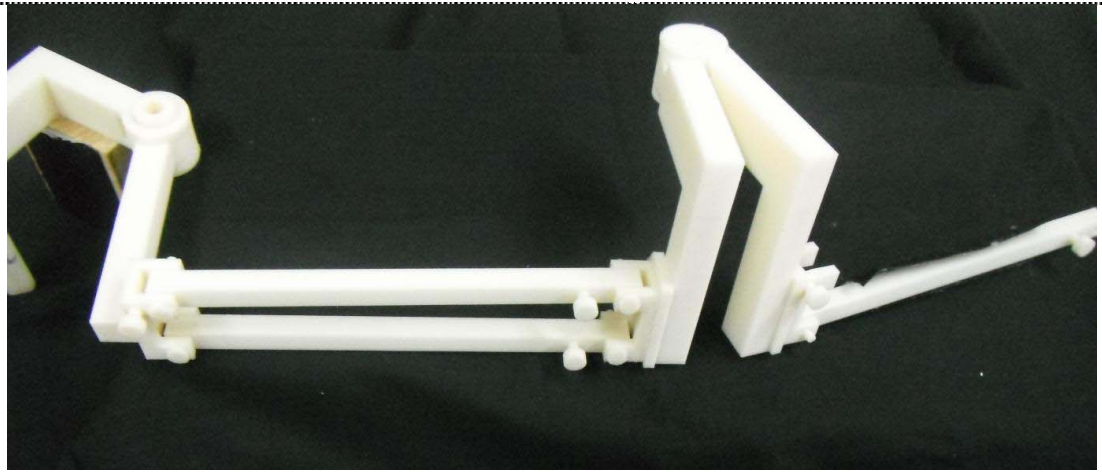


Figure 9. The proposed robotic exoskeleton which incremental rotary encoders will be attached to in order to measure joint angles and speed of joint.

5. Conclusion

A prototype robot joint was fabricated using 3D printing technique with an incremental rotary encoder integrated to measure the angle, direction of rotation and speed of a robotic joint. The developed system is proposed to be integrated into a passive robotic exoskeleton to measure the range and extent of motion of users of this robotic exoskeleton. The measurement system alongside the prototype joint is versatile and suitable to fit a wide variety of applications.

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