MECH420

Sensors and Actuators

Laboratory Manual for Experiment 2

Fall 2020

The University of British Columbia

Department of Mechanical Engineering

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Laboratory Exercise #2: Optical Encoder and Torque Sensor

Learning Objectives

The main objectives of this laboratory exercise are:

- To become familiar with the incremental optical encoder, which is a digital transducer that is used in motion sensing and control,
- To determine static sensor transfer characteristics for a torque sensor,
- To characterize the torque required to run a conveyor belt system, by using an optical encoder and a torque sensor.

Background

Incremental optical encoders and torque sensors are important sensors for monitoring and controlling rotary motion and associated torque, particularly in industrial applications and research. These sensors may be used for monitoring the operation of a mechanical system (e.g., machine) and for performance characterization of system components or the complete system.

1. The Incremental Optical Encoder

Any transducer that generates a *coded* (digital) reading of a measurement (without using an analog-to-digital converter) can be termed an encoder. Shaft encoders are digital transducers that are used for measuring *angular* displacements and *angular* velocities. They generate pulse sequences, which can be converted into digital values (without losing accuracy). High resolution, high accuracy, and relative ease of adoption in digital control systems, with associated reduction in system cost and improvement of system reliability, are some of the relative advantages of digital transducers in general and shaft encoders in particular, in comparison to their analog counterparts. Incremental optical encoders are commercially available integral with dc motors, known as servomotors. These are feedback controlled dc motors, which are appropriate for accurate positioning and motion control applications such as robotics and manufacturing.

The incremental optical encoder is the most common type of shaft encoder. The principal components and operation of an incremental optical encoder are shown in Figure 2.1 [2.1].

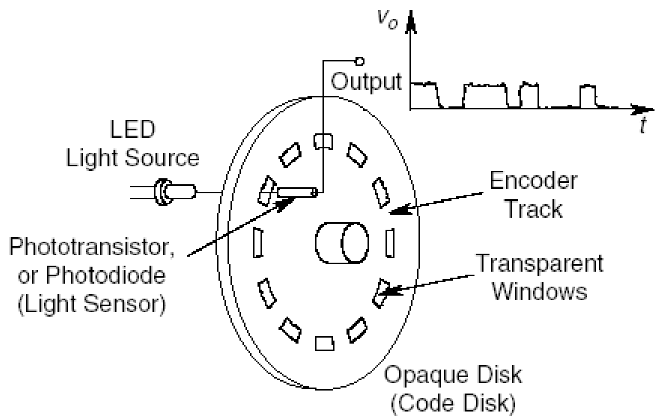


Figure 2.1: Principal components and operation of an incremental optical encoder [2.1].

1.1 Principle of Operation

The optical encoder uses an opaque disk (code disk), which has one or more circular tracks, with transparent windows (slits) in each track. A parallel beam of light (e.g., from a set of light-emitting diodes, or LEDs) is projected to all tracks from one side of the disk. The transmitted light is picked off using a bank of photosensors on the other side of the disk. The arrangement shown in Figure 2.1 indicates just one track and one pick-off sensor. The light sensor may be a silicon photodiode or a phototransistor. Since the light from the source is interrupted by the opaque regions of the track, the output signal from the photosensor is a series of voltage pulses. This signal can be interpreted (e.g., through edge detection or level detection) to obtain the increments in the angular position and also the angular velocity, of the disk.

1.2 Direction of Rotation

In motion control applications it is important to measure the direction as well as the magnitude of motion (i.e., velocity rather than speed). In the simplest configuration, the disk has only a single track with identical and equally spaced windows, where the width of the opaque area between adjacent windows is identical to the window width. Two photosensors (pick-offs 1 and 2) are positioned facing the track at a quarter-pitch (half the window length) apart as shown in Figure 2.2 a [2.1]. Figure 2.2 b and c [2.1] show the output signals (v_1 and v_2) of these photosensors after signal conditioning through pulse-shaping circuitry.

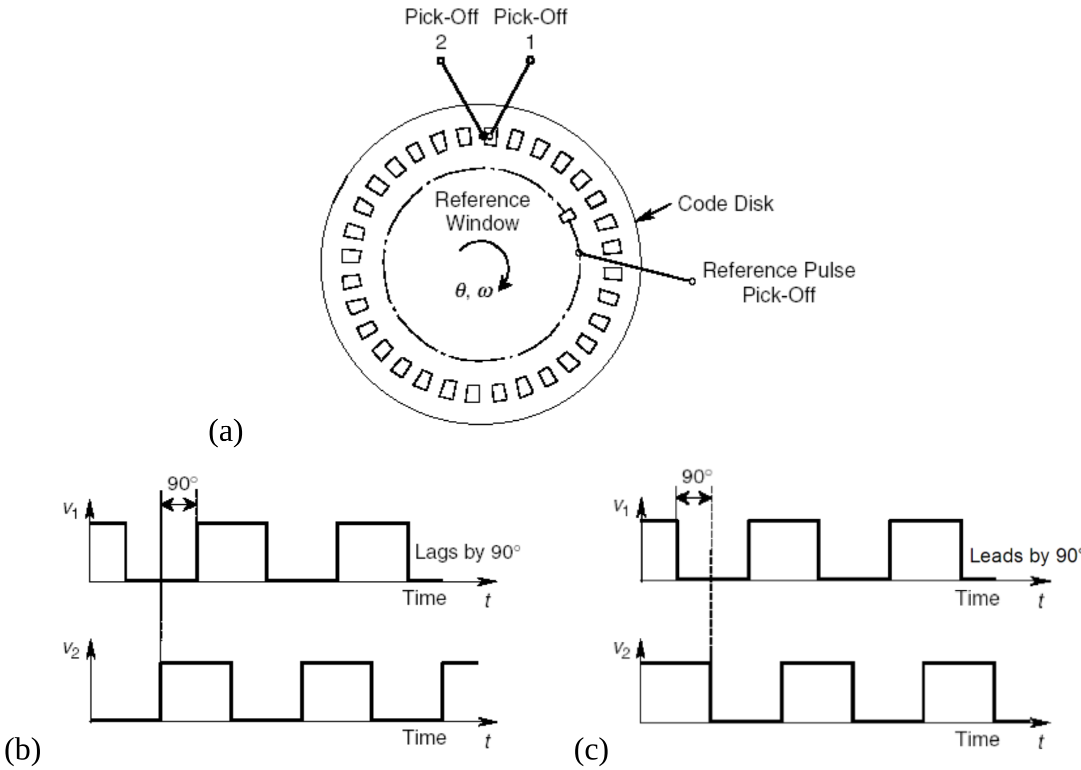


Figure 2.2: Detection of the direction of rotation of an incremental encoder; (a) an encoder disk with a single track and two pick-offs, (b) encoder signal for clockwise rotation, (c) encoder signal for counter-clockwise rotation [2.1].

Specifically, Figure 2.2 b shows the sensor signals when the disk rotates in the clockwise (cw) direction; and Figure 2.2 c shows the outputs when the disk rotates in the counter-clockwise (ccw) direction. It follows from the figure that in cw rotation, v_1 lags v_2 by a quarter of a cycle (i.e., a phase lag of 90°); and in ccw rotation, v_1 leads v_2 by a quarter of a cycle. Thus, these signals are called "quadrature signals" in view of their 90° phase shift. The direction of rotation is obtained by determining the phase difference of the two output signals, using phase-detecting circuitry. One method of accomplishing this is to time (using clock pulses) the interval from the rising edge of one signal to the next rising edge of this signal and also to the next rising edge of the second signal. In general, one of several methods can be used to determine the direction of rotation using the two quadrature signals. For example [2.1],

1. By the phase angle between the two signals
2. By the clock counts between two adjacent rising edges of the two signals
3. By checking for rising or falling edge of one signal when the other is at "high"
4. For a high-to-low transition of one signal, check the next transition of the other signal.

Typically, incremental encoders have an additional *reference* track with one single window and the associated light source and sensor, as shown in Figure 2.2 a. This track generates one pulse per revolution of the disk. This pulse can be used to determine the absolute angular position of the shaft and to count entire revolutions.

An incremental encoder typically has the following 5 pins:

1. Ground
2. Index Channel

3. A Channel
4. +5V DC power
5. B Channel

Pins for Channel A and Channel B give the quadrature signals, and the Index pin gives the reference pulse.

1.3 Angular Displacement Measurement and Resolution

An incremental encoder measures displacement as a pulse count. For N windows spanning an angular range $\hat{\theta}$, a count of n pulses from one pick-off corresponds to an angular displacement,

$$\theta = \frac{n}{N}\hat{\theta}.$$

In addition to the information about the direction of rotation, the quadrature signals give information about the angular position of its shaft. Generally, the physical resolution of an encoder with one single encoder track is the "pitch" of the track (i.e., the angular separation between adjacent windows). However, this resolution can be improved as the angular increment corresponding to one pulse width, or that between the rising edge and the falling edge of a pulse. Furthermore, the resolution can be further improved to ½ the pulse width if opaque and transparent regions of the code disk are distinguished. Hence, it is possible to use the quadrature signals to increase the resolution of the angular position measurement, to ¼ of pitch angle. Specifically, using the quadrature signals of a code disk with N windows around its circumference, the "physical resolution" of displacement measurement is,

$$\Delta\theta = \frac{360°}{4N}$$

1.4 Angular Velocity Measurement

Two methods are available for measuring speed using an incremental encoder:

1. Pulse-counting method
2. Pulse-timing method

In the discussion of these methods we will refer to the signal from a single pick-off generated from either rising or falling edges. In case the quadrature signals are used, the same results are valid with N replaced by $4N$ increments per rotation.

In the pulse-counting method, the pulse count n over a fixed time period T is used to calculate the angular velocity Ω_c. Then, the average time for one pulse is T/n. Since there are N windows on the disk, the angle moved during one pulse is $2\pi / N$. Hence, the angular speed given by $(2\pi / N)/(T / n)$, or

$$\Omega_c = \frac{2\pi n}{NT}$$

This method provides a low accuracy at low velocities.

In the pulse-timing method, the time for one encoder cycle is measured using a high-frequency clock signal of frequency f. If m cycles of the clock signal are counted during an encoder period (i.e., pitch angle), the time for that encoder cycle (i.e., the time to rotate through one encoder pitch) is m/f. With a total of N windows on the track, the angle of rotation during this period is $2\pi / N$. As before, the angular speed is $(2\pi / N)/(m/ f)$, or

$$\Omega_t = \frac{2\pi f}{N m}.$$

This method is particularly suitable for measuring low speeds.

1.5 Angular Velocity Resolution

The velocity resolution is the smallest change in velocity that can be measured. For the pulse counting method, the velocity resolution is given by the difference in velocity corresponding to a pulse count difference $\Delta n = 1$, which is

$$\Delta\Omega_c = \frac{2\pi}{NT}$$

.

For the pulse timing method, the difference in speed corresponding to a clock count increment of $\Delta m = 1$ yields the speed resolution:

$$\Delta\Omega_t = \frac{2\pi f}{N m (m+1)},$$

For large clock cycle counts m, this can be approximated by

$$\Delta\Omega_t \approx \frac{N \Omega_t^{2}}{2\pi f}$$

This resolution, therefore, degrades with the angular velocity Ω_t, as expected.

2. The Torque Sensor

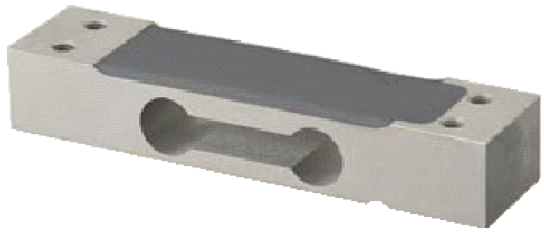
The torque acting on the load by the motor is reacted back on the motor mounts. The two are equal, if we neglect the “inertial torque” due to acceleration of the motor rotor (or if we assume constant angular speed); see [2.1]. A load cell can be used to measure the reaction force on the motor mount, and this can be used to determine the motor torque on the load (under the assumption of constant speed).

Note: In the current experimental setup the torque sensor is mounted between the motor and its mounting plate. The torque measurement is performed through force measurement using two identical load cells.

2.1 The Load Cells

The load cells used for the torque measurement in this experiment are the single point load cells PT1000-7kg marketed by PT Ltd., shown in Fig. 2.3a. Each cell is clamped at one end and the measured force is applied to its opposite end (through a wedge support), as shown in Fig. 2.3b. The metal body of the load cell deforms under the influence of this force (bending moment). The thin regions of the body experience the maximum strain, while the deformation of the thicker regions can be neglected, because the rigidity of a beam to bending depends strongly on its thickness t, according to: $c \sim t^3$.

a)



b)

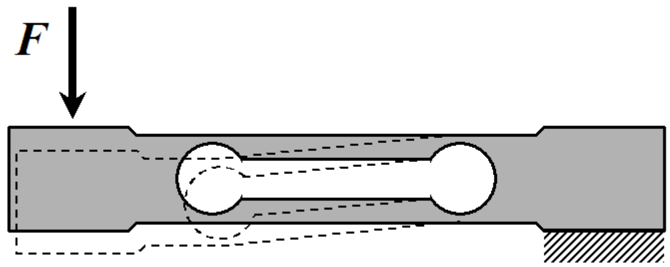


Figure 2.3: Load cell PT1000 from PT Ltd.; (a) a photo; (b) schematic representation of the deformation due to a point force.

As a consequence, the locations of highest strain have been chosen by the manufacturer to mount 4 strain gauges, which are connected in a Wheatstone bridge [4.1], to provide a voltage signal proportional to the strain and hence the applied force.

2.2 The Torque Sensor Assembly

The motor housing is mounted on a fixed bearing plate (base plate) through the load cells. This allows for relative rotation of the motor and the sensor assembly about their common axis. The two load cells are bolted to the motor mount on one of their ends, while their other ends move with the rotation of the motor housing, in both directions (see Fig. 2.4 a). Both load cells are under pre-tension so that they constantly stay in contact with the force contact wedges that are attached to the motor body, as shown in Fig. 2.4 b. The distance from the motor axis to the wedges is $L_L = 57$ mm. For either direction of rotation, the output signal of one load cell increases while the output signal of the other load cell decreases. This occurs because both load cells are pre-loaded to approximately at half of their nominal rating. The difference of these two signals, therefore, measures the magnitude and the direction of the motor torque. The signals are read into the host computer via data acquisition board.

3. The Components of the Experimental Setup

3.1 The Incremental Encoder

The optical encoder used in the experimental setup is model TRD-SH360-VD from Automation Direct. It generates 360 pulses per revolution on both v_1 and v_2 channels, which are the quadrature signals (at 90-degree out of phase). The quadrature output can be obtained from the encoder when it is connected to a quadrature decoder, to obtain the direction of rotation.

3.2 The DC Motor

The motor used in this experiment is model DA34HBB-11 from EAD Motors. It is a brushless DC motor and is powered by a pulse-width modulated (PWM) amplifier [2.1] and an integrated Hall-effect sensor (for motor commutation) [2.1].

3.3 The Load Cells

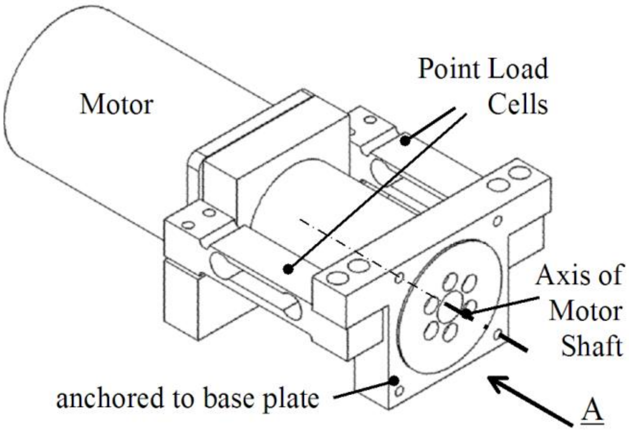
The torque sensor uses two identical load cells of type PT1000-7kg from PT Ltd. The nominal load of the PT1000-7kg cell corresponds to the gravitational force of 7 kg. The nominal bridge output is given by the manufacturer as,

$$\frac{V_{O,N}}{V_S} = 2.165 \text{ mV/V}$$

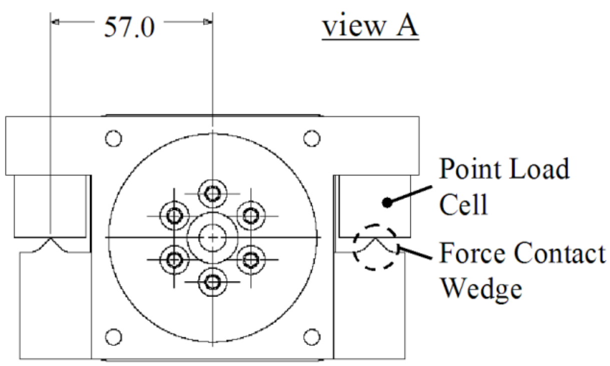
In the present experimental setup the bridge supply voltage is set to $V_S = 10$ V. The voltage signals are amplified using an instrumentation amplifier [2.1] with a gain of 100 before they are acquired by LabVIEW.

3.4 The Torque Reference

A torque arm with two weight holding pins is attached to the torque sensor for calibration purposes, as shown in Figure 2.4c. A set of four weights of approximately 200 gm each is available to load either side of the torque arm. The load pins are located at a distance L_W = 400 mm from the arm's axis of rotation.



a)



b)

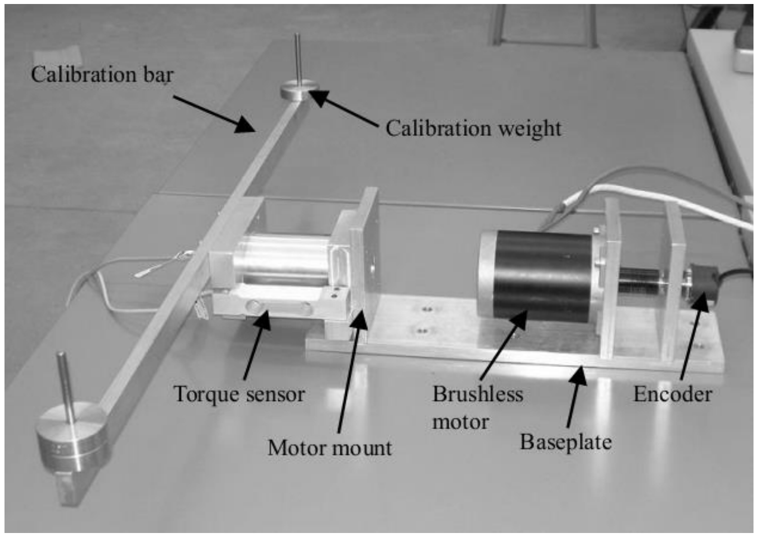
c) 

Figure 2.4: Torque sensor using two load cells; a) the motor-load cell assembly, b) the length of the torque arm (end view), and c) torque sensor calibration setup.

3.5 The Experimental Motor Mount

The torque sensor is attached to the aluminum motor mount bracket for calibration purposes.

3.6 The Conveyor System

The conveyor system consists of a belt, pulleys and a gearbox. A 10:1 (gear ratio) planetary gearbox is used to drive the conveyor, which requires more torque than what the motor would be able to provide directly. In the present experiment, the motor drives the conveyor system, which serves as the load for the motor.

Note: There are other components such as those for grading and ejection of objects on the conveyor, but they are not used in the present experiment.

3.7 The Data Acquisition System

The PC-based, LabVIEW controlled, data acquisition system in the present experiment is identical to the one used in Experiment 1. The data acquisition board has a 16 bit resolution and the voltage range is set to +/- 100 mV for reading the signals from the load cells.

4. Experiments

System component list

1. A brushless DC motor
2. An optical encoder
3. A torque sensor
4. A cantilever bar with a set of weights (the numbers on the weights indicate their mass in gm, each approximately 200 gm)
5. A motor mount bracket
6. A PWM amplifier

7. A data acquisition board (2 channel digital input, 2 channel analog input, 1 channel analog output)
8. Signal conditioning circuitry (200 Hz)
9. A motion control card with an I/O interface board
10. A computer with LabVIEW software system
11. The conveyor system including a gearbox for the motor

Part A: Characterization of the optical encoder signal

Here, we acquired the signals from the optical incremental encoder to see how these signals could be used to determine angular positions and velocities.

Experimental Procedure

1. We attached the brushless DC motor to the motor mount, which is separate from the conveyor system. We attached the encoder to the motor mount and tightened the coupling onto the motor shaft.
2. We connected the encoder and the brushless DC motor to the DAQ board using the DAQ Signal Conditioning Box, as shown in the connection diagram in Fig. 2.6.
3. We opened C:\Mech420\Lab2\Lab2.vi in LabVIEW.
4. We selected the Mode “Rotate By Hand” and set the Motor 1 Reference voltage to zero, and made sure that the motor power supply was turned off. We rotated the motor shaft by hand in one direction and recorded the corresponding encoder signals (1000 samples) by simultaneously pressing the Acquire Encoder Data button. Also, we noted the direction of rotation of the encoder. Then we recorded a reasonable number of samples at a reasonable data acquisition frequency.
5. We repeated step 4, by rotating the motor shaft in the opposite direction.
6. We pushed the Stop button. The data for each direction was recorded in a separate Excel file. We saved both files. These files are provided to you so you can analyze the data, for your report.
7. We ran the program again.
8. We selected the Mode “Rotate By Motor” and turned on the motor power supply. Then we ran the brushless DC motor in open loop mode without load by setting the Motor 1 Reference box on the front panel to 0.5V.
9. When the motor reached a constant velocity, we pressed the Acquire Encoder Data button. This triggered the DAQ board to acquire 1000 samples from the encoder at 400 kHz (this is the set data acquisition rate).
10. Once the samples have been gathered, the program automatically stored the data in a new Excel file. We have saved this file. This file is provided it to you, so you can analyze the data for your report. Motor 1 Reference voltage has been noted in the file name.
11. We repeat this procedure for 2 additional motor voltages in the range 0.51-1.0 V.

12. We pressed the Stop button.

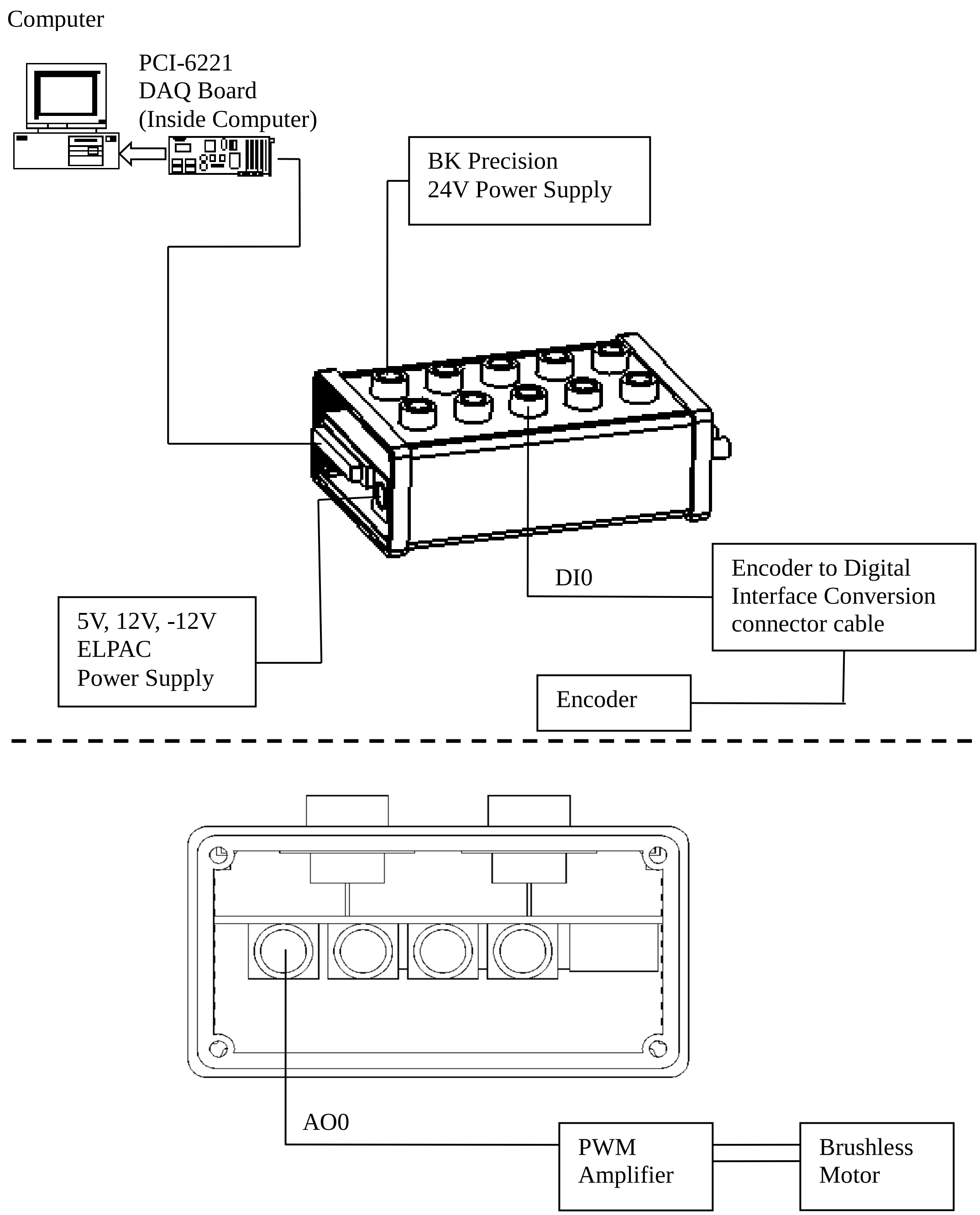


Figure 2.6: Connection Diagram for Lab #2, Part A.

Data Analysis (for your lab report)

1. For both directions of rotation of the encoder shaft provide one plot with the encoder phases (the two pick-off signals) as a function of time for a few encoder increments.
2. Comment on the measurement of the direction of rotation.

3. Calculate the rotational speed of the motor for the different excitation voltages from the encoder signals using both the pulse counting method and the pulse timing method. Calculate the velocity resolution for each measurement. For the pulse timing method, compare the exact value of the resolution with the approximate value (assuming the number of clock pulses m for one encoder increment is large).

Part B: Characterization of the Torque Sensor

In this part, we will calibrate the torque sensor and determine its “static” transfer characteristics. You will determine how this measured transfer characteristic relates to the transfer characteristics of its two load cells as given by the manufacturer (you have to obtain this. See Section 5, Additional Exercises). One of the characteristics you will determine is hysteresis. For this purpose, you will need to compare the behavior when adding and removing the weights.

Experimental Procedure

1. We attached the torque sensor to the motor mount, which is separate from the conveyor system.
2. We connected the load cells to the DAQ Signal Conditioning Box, as shown in the connection diagram in Fig. 2.7.
3. We selected the Part B tab in Lab2.vi in LabVIEW.
4. We ran the program.
5. We attached the cantilever bar to the motor mounting face of the torque sensor. The torque applied by the cantilever bar would be close to zero now. We entered a torque of 0 into the “Applied Torque” box. We clicked the “Acquire Torque Data” button. This triggered the DAQ board to acquire 25 samples from the torque sensor at 1 kHz. The software collected 25 samples each time we pressed the “Acquire Torque Data” button. We stored this data by pressing the STOP button. *Note*: We can either store all data in separate files (by pressing “STOP” after each acquisition step) or in one file (by pressing “STOP” only at the end). We have saved the data file(s), which are provided to you.
6. We carefully added one weight to one end of the torque calibration arm and calculated the torque that this applied. We entered the value into the Applied Torque box. We clicked the Acquire Torque Data button.
7. We gradually increased the torque and acquired the torque data until we have used all four weights.
8. Now carefully removed the weights one by one, taking torque readings in the same way as we did before. *Note*: The difference in behavior when adding and removing the weights will help you to characterise hysteresis in the system.
9. We repeated steps 6 to 8 using the opposite end of the torque arm.
10. We repeated steps 6 to 9, to record the full data set twice.

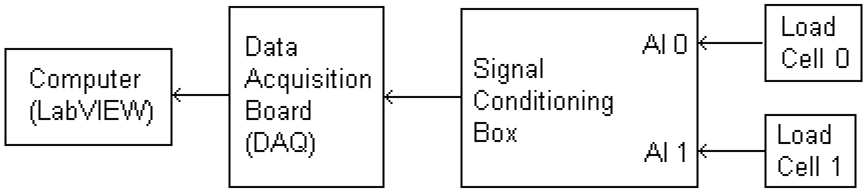


Figure 2.7: Part B Connection Diagram.

Data Analysis (for your lab report)

1. Plot the torque sensor signal as a function of the torque applied by the weights. Remember to use the difference in voltage between the two load cells.
2. Calculate the "least squares" [2.1] linear calibration curve $V_T(T)$ for the torque sensor using the sensor signals from the second load cycle only.
3. Determine and plot the absolute nonlinearity error [2.1] and the absolute hysteresis error of the torque sensor for the data from the second load cycle.
4. Compare the theoretical and measured sensitivity, offset, and absolute nonlinearity and hysteresis errors of the torque sensor. Use the absolute errors, not relative errors.

Note: Error considerations and analysis will be covered in the course. But, since the lab exercise may be done before that, you will have to do some self-study here. You may review the appropriate sections of the textbook and/or other sources to get the necessary knowledge for this purpose.

Part C: Measurement of the Torque Required to Drive the Conveyor

In this part, we use the torque sensor calibration to determine the torque necessary to drive the conveyor belt system at a given speed. The motor speed can be automatically set using a velocity feedback loop provided by the LabVIEW program (which is already prepared).

Experimental Procedure

1. We set up the motor using the motion control card, torque sensor, and gearbox to run the conveyor.
2. We selected the Part C tab.
3. We set the data acquisition rate to about 30 Hz.
4. We ran the program.
5. Using the Pulley Speed (RPM) box on the front panel, we selected a speed between 30 and 55 rpm. We waited until the conveyor reached a constant speed. *Note*: Since the gearbox has a reduction ratio of 10:1, the actual speed of the motor is 300 to 550 rpm.
6. We chose a reference point along the conveyor. When the belt splicing reached this reference point, we clicked the Start Torque Acquisition button to begin acquiring data from the torque sensor. We let the belt run for two full cycles. When the belt splicing again reached the reference point, we clicked the Stop

Acquisition button. After all the data has been acquired, we clicked the END PROGAM button on the front panel.

7. We viewed the MS Excel file that had opened in the task bar. This file contained all the acquired data. We have saved this file. This file is provided to you, for analysis and completing the lab report.

Data Analysis (for your lab report)

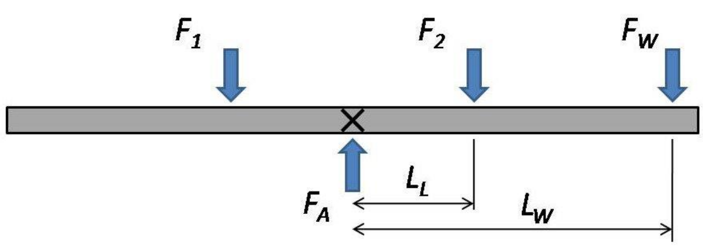
Plot the torque of the motor on the gearbox and conveyor system for one cycle of the conveyor system. (Use the sensor "static" transfer function determined previously.) Calculate the average and the standard deviation of the torque.

5. Additional Exercises (These should be included at the end of your report)

1. Assume that you use the quadrature signals of an optical encoder with 360 windows, and timing frequency of 400 Hz, and a counting period of 2.5 ms. Determine the angular velocity at which the velocity resolution for both pulse counting and for pulse timing is identical; assume the simplified formula for the pulse timing method. Which method will be more accurate at higher rotational velocities?

2. Determine the "static" transfer characteristics of the torque sensor through the following steps (you may use the data given in this Lab Manual and also the information given in the data sheet of the load cell PT1000-7kg cell (you must search and obtain this data sheet):

- Use the free body diagram in Fig. 2.5 for the torque arm of the torque calibration bar, including the applied weight F_W and the forces F_1 and F_2 applied to the load cells of the torque sensor as well as the vertical load onto the motor shaft F_A. Determine the torque T applied to the motor mount by the weights on the torque arm in terms of the forces F_1 and F_2.



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- Figure 2.5 – Free body diagram for the torque sensor in Experiment 2.

- Provide expressions for the voltages V_1 and V_2 at the output of the two load cells as a function of the forces F_1 and F_2, the sensitivities B_1 and B_2, the offsets V_{10} and V_{20} of the load cell outputs, and the errors ΔV_1 and ΔV_2.

- The output voltage of the torque sensor is the amplified (gain G) difference between the output voltages of both load cells. Write down this voltage as a function of the torque T assuming an identical sensitivity for both load cells

- From this expression determine the expression for sensitivity S of the torque sensor and determine its numerical value (including units!) using the data sheet and the geometry of the setup, keeping in mind that the supply voltage for the load cells is 10 V.

- Determine the maximum expected offset voltage of the torque sensor using the data sheet for the load cells.
- Also, estimate the maximum nonlinearity error and the hysteresis error of the torque sensor in terms of output voltage using the data sheet for the load cells.

Note: In the last two items in this exercise (2), you may use the "Absolute" method rather than the "Square-root of Sum of Squares (SRSS)" method of error combination (See Section 3.9 of the textbook [2.1]).

3. Search and obtain the data sheets and images of the following items (not those used in the present experiment): 1. A DC motor with a built-in encoder; 2. A PWM amplifier (or drive hardware) for the motor; 3. A microcontroller. Suppose that the microcontroller is programmed to acquire the signals from the motor encoder, and based on that information and the required motion profile, a signal is generated for the PWM amplifier to drive the motor accordingly. Provide a schematic diagram that contains the images of these three components and any other required hardware for this system. In the diagram, show how the components are interconnected, using lines to represent cable strands (signal paths). *Note*: No knowledge on programming the microcontroller, how to properly match the components, and how to operate the system, is needed to be included here. Only the interconnection details of the components should be presented.

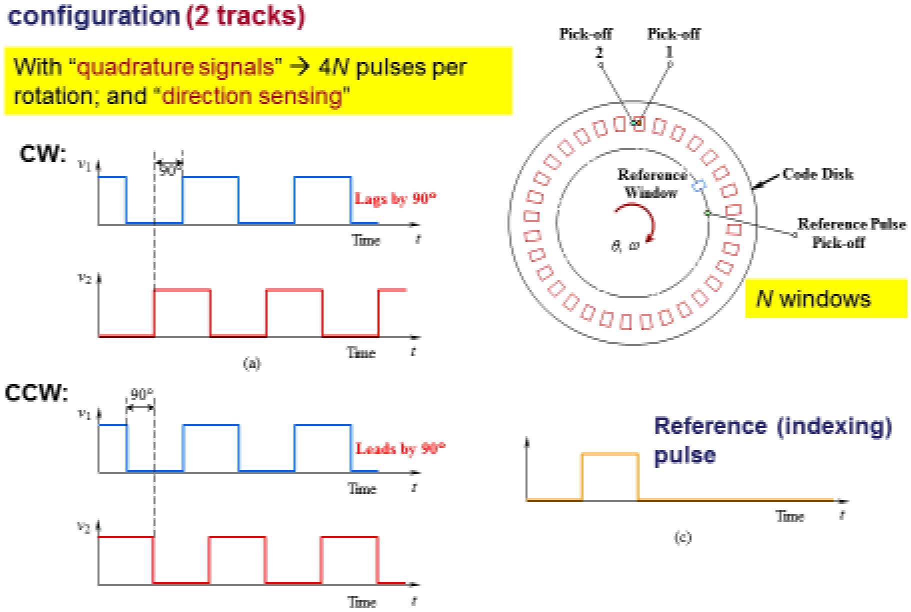
Reference

[2.1] *Sensors and Actuators: Engineering System Instrumentation*, 2nd Edition, C. W. de Silva, CRC Press, Taylor & Francis, Boca Raton, FL, ISBN: 978-1-4665-0681-7, 2016.

Incremental Optical Encoder Signals

Two types: 1. Offset sensor configuration (2 sensors); 2. Offset track configuration (2 tracks)

With "quadrature signals" → 4*N* pulses per rotation; and "direction sensing"

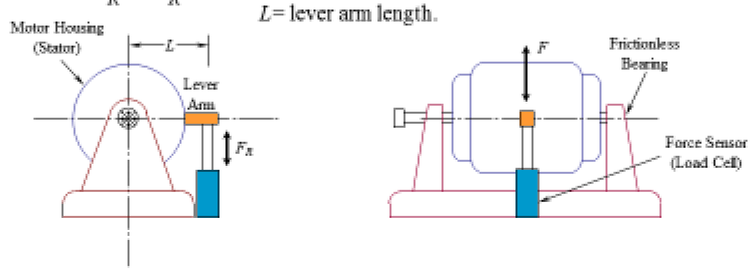


Reaction Torque Sensor

- **Disadvantages of Direct Torque Sensing:** The sensing element connected to motor shaft will modify the original system: Reduces the system stiffness, decreases the system bandwidth, and adds extra loading
- **Another Disadvantage:** Torque sensing is done on a rotating element (shaft)
- Reaction torque sensor eliminates these problems
- **Method:** Housing of the rotating machine is cradled; effort necessary to keep the structure stationary is measured.

$T_R = F_R \cdot L$ F_R = reaction force measured using load cell

L = lever arm length.



Data Sheet for PT1000-7kg Load Cell

Specifications

Note: All specifications are a maximum, as a % (±) of full load, unless otherwise stated.

Nominal Capacity	3kg – 250kg	Input Impedance	425Ω ± 15Ω
Signal Output at Capacity	2mV/V ± 10%	Output Impedance	350Ω ± 3Ω
Linearity Error	< 0.020% FSO	Insulation Impedance	> 5000 MΩ at 100V DC
Non-Repeatability	< 0.010% FSO	Excitation Voltage (Recommended)	5 – 12V AC/DC
Combined Error	< 0.025% FSO	Excitation Voltage (Maximum)	15V AC/DC
Hysteresis	< 0.015% FSO	Eccentric Loading (effect/cm)	< 0.0085% FSO (3 – 35kg)
Creep/Zero Return (30 mins)	< 0.030% / 0.020% FSO		< 0.0074% FSO (50 – 250kg)
Zero Balanc	< 3.000% Capacity	Deflection at Rated Capacity	< 0.4mm
Temperature Effect on Span/10°C	< 0.010% FSO	Storage Temperature Range	-50 ~ 70°C
Temperature Effect on Zero/10°C	< 0.015% Capacity	Cable Type	4mm, Screened, PVC Sheath
Compensated Temperature Range	-10 ~ 40°C		4 Core x 0.09mm² (28 AWG)
Operating Temperature Range	-30 – 70°C	Cable Length	0.5 Metre (3kg – 35kg)
Service Load	100% of Rated Capacity		1 Metre (50kg – 250kg)
Safe Load	150% of Rated Capacity	Material	Aluminium
Ultimate Load	300% of Rated Capacity	Finish	Marine Anodised