NANYANG TECHNOLOGICAL UNIVERSITY

SEMESTER 2 EXAMINATION 2020-2021

MA2012 - INTRODUCTION TO MECHATRONICS SYSTEMS DESIGN

April/May 2021 Time: 2 hours

INSTRUCTIONS:

1. This paper contains **SECTION A & SECTION B** and comprises of **ELEVEN (11)** pages including **SIX (6)** pages of Appendices..
2. **COMPULSORY** to answer **ALL** questions in both sections.
3. All question carries equal marks.
4. This is a **CLOSED-BOOK** examination.

Section A

1. You are to design a mechatronic system to control a 'Wheel of Fortune' game at an amusement park (see Figure 1). In this game, the player can press one of the two buttons labelled '1' or '2' to start spinning the wheel in counter-clockwise or clockwise direction respectively. Once the button is released, the wheel will slowly come to its natural stop. If a white sector lands on the Prize Indicator which is pointing at the 12 o'clock position, a prize is won. The level of prize depends on the width of the sector, the smaller the sector, the higher the prize, with the top prize being a 1° wide sector. The system consists of 3 sub-systems, each controlled by an Arduino UNO MCU.

   (a) Player Controller. The handheld device is powered by battery and communicate with the Wheel Controller via Bluetooth. It has 1 toggle power switch, 2 pushbuttons to spin the wheel and 1 LED indicator light.

   (b) Wheel Controller. The wheel has 19 sectors, and its axis of rotation is in the horizontal plane. The rotation is controlled by a 12V DC motor, an incremental encoder to determine the angular displacement of the wheel and the prize won, 1 array of 19 LEDs – one for each sector (prize). The Wheel Controller communicates with the Player Controller via Bluetooth and with the Display Unit via the MCU's built-in UART. It also has 1 toggle power switch and 1 power indicator LED.

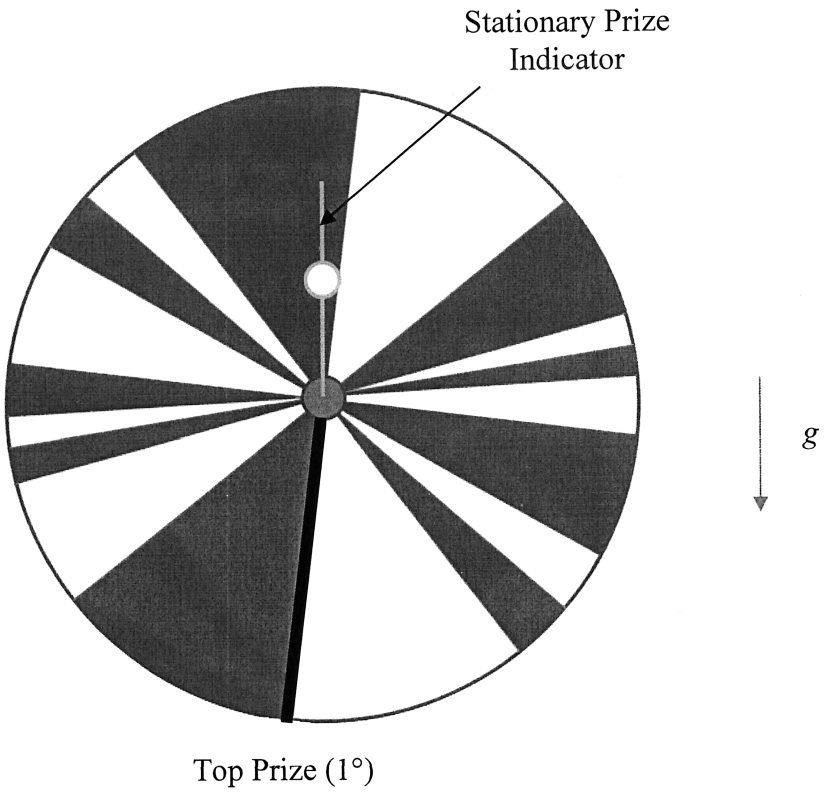
   (c) Display Unit. The unit has a 32-character LCD, a potentiometer to control the brightness of the LCD, and 1 toggle power switch. It communicates with the Wheel Controller via the MCU's built-in UART.

Note: Question 1 continues on page 2.
Figure 1 appears on page 2.

Sketch a schematic block diagram to show your design of the control systems for this application. Indicate and describe clearly in your diagram all the mechatronic components (Arduino UNO MCUs, sensors, actuators, I/O devices, interfacing devices, power sources, etc.) and their relationships to each other. You may make appropriate assumptions to add new components (e.g. switches), but you need to state them clearly.

Your answer need to specify only the component type. Information on the make and model of components are <u>not</u> necessary.

(25 marks)



<u>Figure 1:</u> The spinning wheel of a 'Wheel of Fortune' game.

2. Study the datasheet of an incremental encoder provided in Appendix A. It is decided that model E6C3-CWZ3EH 360P/R 1M is to be used for the application in Question 1.

(a) Sketch a circuit diagram to show how you would interface this encoder with an Arduino UNO MCU.

(6 marks)

(b) The command –

attachInterrupt(digitalPinToInterrupt(pin), ISR, mode);

is to be used by the MCU to sense the pulses generated by the encoder.

(i) Explain why using 'interrupt' is an appropriate way to interface with an encoder.

(3 marks)

(ii) Based on your circuit diagram in Part (a), complete the *attachInterrupt* command. (Note: ISR = Interrupt Service Routine, mode = RISING or FALLING)

(3 marks)

(iii) Write C++ codes for the ISR to update the current position of the incremental encoder, by considering the direction of rotation.

(6 marks)

(c) Describe how you would calculate the speed of rotation.

(3 marks)

(d) How would you use Phase Z in this application?

(4 marks)

Section B

3. It is suggested that an analog dual axes accelerometer (Vcc = 5.0V) may be used to replace the incremental encoder. The accelerometer's X_{out} and Y_{out} pins output 2.50V at 0 *g*, have a sensitivity of 1.25V per *g* and a range of ± 2 *g*. They are interfaced with the Analog Input pins of the Arduino UNO MCU.

(a) The accelerometer is intended to be used in a way where both its sensing axes Ax and Ay are in the gravity plane, as shown in Figure 2. Determine the tilt angle sensing resolution (i.e. the smallest detectable change in tilt angle) of Ax and Ay at this configuration.

(10 marks)

(b) The accelerometer is rotated by +45° about the axis of rotation from the position shown in Figure 2. Repeat the calculation of tilt angle sensing resolution of Ax and Ay at this configuration.

(8 marks)

(c) The application in Question 1 requires the sensor to accurately measure angular displacement of 1 degree resolution. Without considering more advanced signal processing techniques, would the sensing resolution of this accelerometer be adequate for this application? Explain your answer.

(4 marks)

(d) Would your answer in Part (c) be different if there are zero-offsets of +0.05V in both the Xout and Yout pins? Explain your answer.

(3 marks)

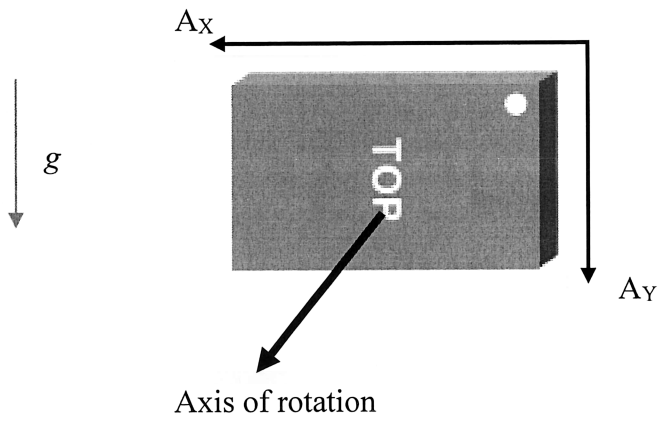


Figure 2: Dual axes accelerometer orient in the gravity plane

4. An unipolar stepper motor is under consideration to replace the DC motor for the application in Question 1.

(a) Name 1 advantage of using a stepper motor over a DC motor in this application?
(2 marks)

(b) There are two modes to drive the stepper motor: Two Phase Full Step or Two Phase Half Step. Discuss the comparative advantages of each of the driving modes.
(4 marks)

(c) If Two Phase Half Step driving mode is used, what would be the minimum specification of the stepper motor in term of steps per revolution?
(2 marks)

(d) If the only stepper motor available has only 50% of the required minimum stepping resolution, the technique of microstepping may be used to drive the stepper motor. Explain the working principle of microstepping.
(4 marks)

(e) If a stepper driver is not available, we may interface the stepper motor with the MCU using 4 BUZ11 transistors as shown in Figure 3. Describe the sequence of turning the transistors ON and OFF to drive the stepper motor in both directions with using Two Phase Half Step mode. You may present your answer in a table format.
(13 marks)

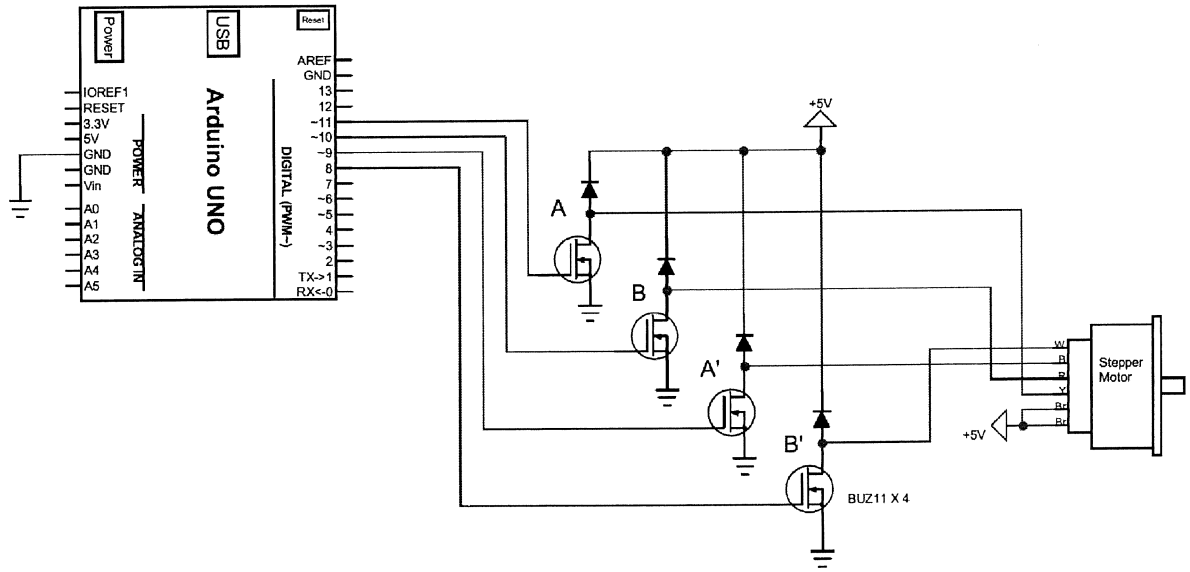


Figure 3: Interfacing a stepper motor with Arduino UNO using 4 transistors.

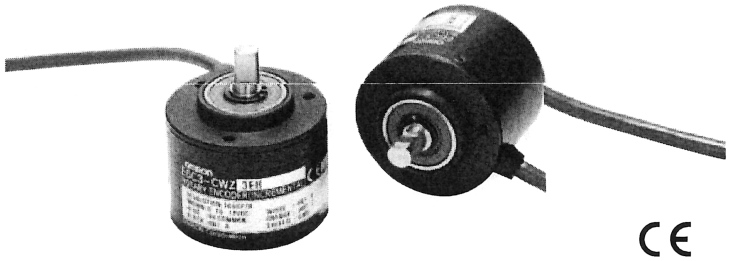
Rugged Incremental 50-mm-dia. Rotary Encoder

E6C3-C

E6C3-C_DS_E_7_1

Rugged Rotary Encoder

- Incremental model
- External diameter of 50 mm.
- Resolution of up to 3,600 ppr.
- IP65 (improved oil-proof construction with sealed bearings)
- Superior shaft loading performance (radial: 80 N, thrust: 50 N)



⚠ Be sure to read *Safety Precautions* on page 4.

Ordering Information

Encoders [Refer to *Dimensions* on page 4.]

Power supply voltage	Output configuration	Resolution (pulses/rotation)	Connection method	Model
12 to 24 VDC	Complementary output	100, 200, 300, 360, 500, 600, 720, 800, 1,000, 1,024, 1,200, 1,500, 1,800, 2,000, 2,048, 2,500, 3,600	Pre-wired (1 m) (See note.)	**E6C3-CWZ5GH (resolution) 1M** Example: E6C3-CWZ5GH 100P/R 1M
5 to 12 VDC	Voltage output	100, 200, 300, 360, 500, 600, 720, 800, 1,000, 1,024, 1,200, 1,500, 1,800, 2,000, 2,048, 2,500, 3,600		**E6C3-CWZ3EH (resolution) 1M** Example: E6C3-CWZ3EH 100P/R 1M
5 to 12 VDC	Line-driver output	100, 200, 300, 360, 500, 600, 720, 800, 1,000, 1,024, 1,200, 1,500, 1,800, 2,000, 2,048, 2,500, 3,600		**E6C3-CWZ3XH (resolution) 1M** Example: E6C3-CWZ3XH 100P/R 1M

Note: Models with 2-m cable are also available. When ordering, specify the cable length at the end of the model number (example: E6C3-CWZ5GH 300P/R 2M).

Accessories (Order Separately) [Refer to *Dimensions* on *Rotary Encoder Accessories*.]

Name	Model	Remarks
Couplings	**E69-C08B**	---
	E69-C68B	Different end diameter (6 to 8 mm)
Flanges	**E69-FCA03**	---
	E69-FCA04	E69-2 Servo Mounting Bracket provided.
Servo Mounting Bracket	**E69-2**	Provided with E69-FCA04 Flange.

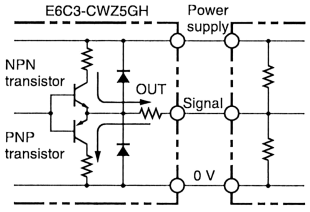
Refer to *Accessories* for details.

Ratings and Specifications

Item \ Model		E6C3-CWZ5GH	E6C3-CWZ3EH	E6C3-CWZ3XH
Power supply voltage		12 VDC –10% to 24 VDC +15%, ripple (p-p): 5% max.	5 VDC –5% to 12 VDC +10%, ripple (p-p): 5% max.	
Current consumption*1		100 mA max.		
Resolution (pulses/rotation)		100, 200, 300, 360, 500, 600, 720, 800, 1,000, 1,024, 1,200, 1,500, 1,800, 2,000, 2,048, 2,500, 3,600		
Output phases		Phases A, B, and Z*5		Phases A, $\overline{A}$, B, $\overline{B}$, Z, and $\overline{Z}$
Output configuration		Complementary outputs*2	Voltage output (NPN output)	Line driver output*3
Output capacity		Output voltage: VH = Vcc -3 V min. (IO = 30 mA) VL = 2 V max. (IO = –30 mA) Output current: ±30 mA	Output resistance: 2 kΩ Output current: 35 mA max. Residual voltage: 0.7 V max.	AM26LS31 equivalent Output current: High level: IO = –10 mA Low level: IS = 10 mA Output voltage: VO = 2.5 V min. VS = 0.5 V max.
Maximum response frequency*4		125 kHz (65 kHz when using phase Z reset)		
Phase difference between outputs		90°±45° between A and B (1/4 T ± 1/8 T)		
Rise and fall times of output		1 µs max. (Cable length: 2 m, Output current: 30 mA)	1 µs max. (Cable length: 2 m, Output current: 35 mA)	1 µs max. (Cable length: 2 m, IO: –10 mA, IS: 10 mA)
Starting torque		10 mN·m max. at room temperature, 30 mN·m max. at low temperature		
Moment of inertia		2.0×10^{-6} kg·m² max.; 1.9×10^{-6} kg·m² max. at 500 P/R max.		
Shaft loading	Radial	80 N		
	Thrust	50 N		
Maximum permissible speed		5,000 r/min		
Protection circuits		Power supply reverse polarity protection, Output load short-circuit protection		---
Ambient temperature range		Operating: –10 to 70°C (with no icing), Storage: –25 to 85°C (with no icing)		
Ambient humidity range		Operating/Storage: 35% to 85% (with no condensation)		
Insulation resistance		20 MΩ min. (at 500 VDC) between current-carrying parts and case		
Dielectric strength		500 VAC, 50/60 Hz for 1 min between current-carrying parts and case		
Vibration resistance		Destruction: 10 to 500 Hz, 150 m/s² or 2-mm double amplitude for 11 min 3 times each in X, Y, and Z directions		
Shock resistance		Destruction: 1,000 m/s² 3 times each in X, Y, and Z directions		
Degree of protection		IEC 60529 IP65, in-house standards: oilproof		
Connection method		Pre-wired Models (Standard cable length: 1 m)		
Material		Case: Aluminum, Main unit: Aluminum, Shaft: SUS303		
Weight (packed state)		Approx. 300 g		
Accessories		Instruction manual Note: Coupling, mounting bracket and hex-head spanner are sold separately.		

*1. An inrush current of approximately 9 A will flow for approximately 0.1 ms when the power is turned ON.

*2. Complementary Output
The complementary output has two output transistors (NPN and PNP) as shown below. These two output transistors alternately turn ON and OFF depending on the high or low output signal. When using them, pull up to the positive power supply voltage level or pull down to 0 V. The complementary output allows flow-in or flow-out of the output current and thus the rising and falling speeds of signals are fast. This allows a long cable distance. They can be connected to open-collector input devices (NPN, PNP).



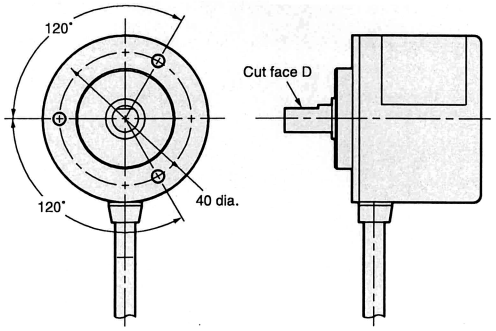
*3. The line driver output is a data transmission circuit compatible with RS-422A and long-distance transmission is possible with a twisted-pair cable. (AM26LS31 equivalent)

*4. The maximum electrical response speed is determined by the resolution and maximum response frequency as follows:

$$\text{Maximum electrical response speed (rpm)} = \frac{\text{Maximum response frequency}}{\text{Resolution}} \times 60$$

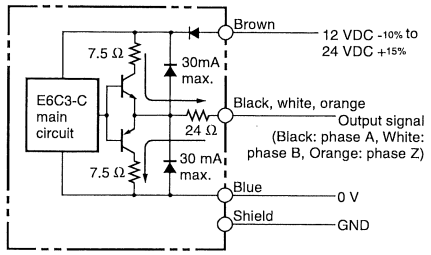
This means that the Rotary Encoder will not operate electrically if its speed exceeds the maximum electrical response speed.

*5. The phase Z signal is output when cut face D on the shaft and the cable connection direction are as shown in the following diagram (output position range: ±15°).

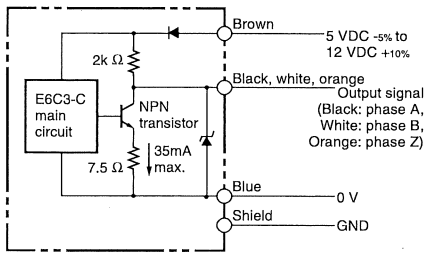


I/O Circuit Diagrams

E6C3-CWZ5GH

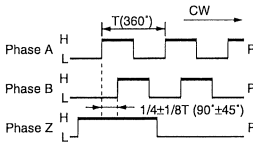


E6C3-CWZ3EH



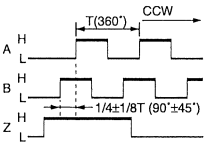
E6C3-CWZ5GH Voltage Output Model
E6C3-CWZ5GH Complementary Output Model

Direction of rotation: CW (as viewed from end of shaft)



Note: Phase A is 1/4 T ± 1/8 T faster than phase B.

Direction of rotation: CCW (as viewed from end of shaft)

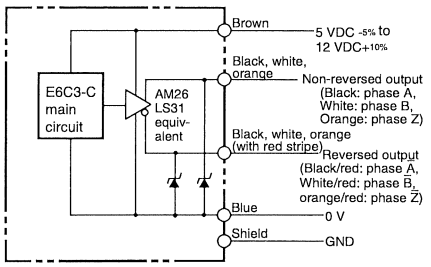


Note: Phase A is 1/4 T ± 1/8 T slower than phase B.

("H" and "L" in the diagrams are the output voltage levels of phases A, B, and Z.)

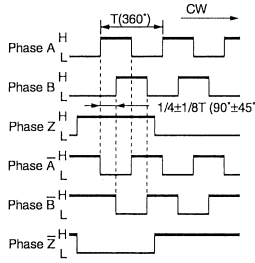
Color	Terminal
Brown	Power supply (+Vcc)
Black	Output phase A
White	Output phase B
Orange	Output phase Z
Blue	0 V (common)

E6C3-CWZ3XH



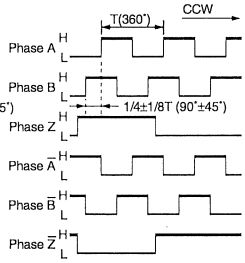
E6C3-CWZ3XH Line Driver Output Model

Direction of rotation: CW (as viewed from end of shaft)



Note: Phase A is 1/4 T ± 1/8 T faster than phase B.

Direction of rotation: CCW (as viewed from end of shaft)



Note: Phase A is 1/4 T ± 1/8 T slower than phase B.

("H" and "L" in the diagrams are the output voltage levels of phases A, B, and Z.)

Color	Terminal
Brown	Power supply (+Vcc)
Black	Output phase A
White	Output phase B
Orange	Output phase Z
Black/red stripes	Output phase Ā
White/red stripes	Output phase B̄
Orange/ red stripes	Output phase Z̄
Blue	0 V (common)

Note: Receiver: AM26LS32 equivalent

Note: 1. The shielded cable outer core (shield) is not connected to the inner area or to the case.
2. The phase A, phase B, and phase Z circuits are all identical.
3. Normally, connect GND to 0 V or to an external ground.

Safety Precautions

Refer to *Warranty and Limitations of Liability*.

⚠ WARNING

This product is not designed or rated for ensuring safety of persons either directly or indirectly. Do not use it for such purposes.

Precautions for Correct Use

Do not use the Encoder under ambient conditions that exceed the ratings.

● Wiring

Connections

Cable Extension Characteristics

- When the cable length is extended, the output waveform startup time is lengthened and it affects the phase difference characteristics of phases A and B. Conditions will change according to frequency, noise, and other factors. As a guideline, use a cable length of 10 m* or less. If the cable must be more than 10 m, use a Model with a Line-driver Output or Complementary Output.
  (max. length for line-driver output: 100 m,
  max. length for complementary output: 30 m)

* Recommended Cable
Conductor cross section: 0.2 mm²
Spiral shield
Conductor resistance: 92 Ω/km max. (20°C)
Insulation resistance: 5 Ω/km min. (20°C)

- The output waveform startup time changes not only according to the length of the cable, but also according to the load resistance and the cable type.
- Extending the cable length not only changes the startup time, but also increases the output residual voltage.

● Connection

Spurious pulses may be generated when power is turned ON and OFF. Wait at least 0.1 s after turning ON the power to the Encoder before using the connected device, and stop using the connected device at least 0.1 s before turning OFF the power to the Encoder. Also, turn ON the power to the load only after turning ON the power to the Encoder.

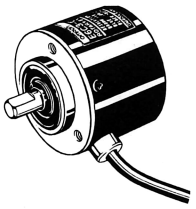
(Unit: mm)

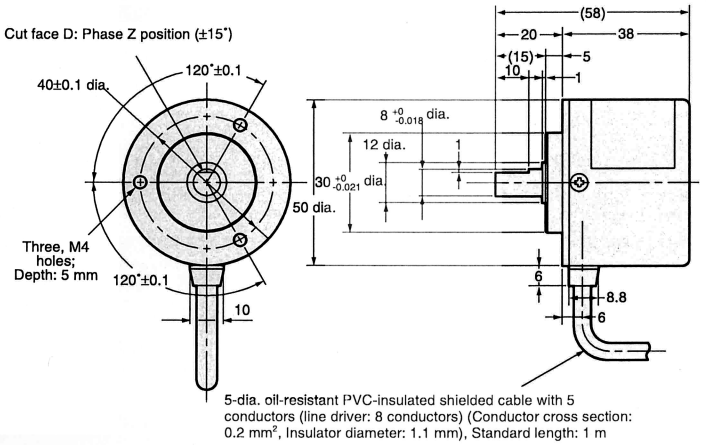
Dimensions

Tolerance class IT16 applies to dimensions in this datasheet unless otherwise specified.

Encoder

E6C3-CWZ□□H





The E69-C08B Coupling is sold separately.

Accessories (Order Separately)

Couplings	Flanges
E69-C08B	E69-FCA03
E69-C68B	E69-FCA04

Servo Mounting Bracket

E69-2

Refer to *Accessories* for details.

Terms and Conditions of Sale

1. Offer; Acceptance. These terms and conditions (these "Terms") are deemed part of all quotes, agreements, purchase orders, acknowledgments, price lists, catalogs, manuals, brochures and other documents, whether electronic or in writing, relating to the sale of products or services (collectively, the "Products") by Omron Electronics LLC and its subsidiary companies ("Omron"). Omron objects to any terms or conditions proposed in Buyer's purchase order or other documents which are inconsistent with, or in addition to, these Terms.
2. Prices; Payment Terms. All prices stated are current, subject to change without notice by Omron. Omron reserves the right to increase or decrease prices on any unshipped portions of outstanding orders. Payments for Products are due net 30 days unless otherwise stated in the invoice.
3. Discounts. Cash discounts, if any, will apply only on the net amount of invoices sent to Buyer after deducting transportation charges, taxes and duties, and will be allowed only if (i) the invoice is paid according to Omron's payment terms and (ii) Buyer has no past due amounts.
4. Interest. Omron, at its option, may charge Buyer 1-1/2% interest per month or the maximum legal rate, whichever is less, on any balance not paid within the stated terms.
5. Orders. Omron will accept no order less than $200 net billing.
6. Governmental Approvals. Buyer shall be responsible for, and shall bear all costs involved in, obtaining any government approvals required for the importation or sale of the Products.
7. Taxes. All taxes, duties and other governmental charges (other than general real property and income taxes), including any interest or penalties thereon, imposed directly or indirectly on Omron or required to be collected directly or indirectly by Omron for the manufacture, production, sale, delivery, importation, consumption or use of the Products sold hereunder (including customs duties and sales, excise, use, turnover and license taxes) shall be charged to and remitted by Buyer to Omron.
8. Financial. If the financial position of Buyer at any time becomes unsatisfactory to Omron, Omron reserves the right to stop shipments or require satisfactory security or payment in advance. If Buyer fails to make payment or otherwise comply with these Terms or any related agreement, Omron may (without liability and in addition to other remedies) cancel any unshipped portion of Products sold hereunder and stop any Products in transit until Buyer pays all amounts, including amounts payable hereunder, whether or not then due, which are owing to it by Buyer. Buyer shall in any event remain liable for all unpaid accounts.
9. Cancellation; Etc. Orders are not subject to rescheduling or cancellation unless Buyer indemnifies Omron against all related costs or expenses.
10. Force Majeure. Omron shall not be liable for any delay or failure in delivery resulting from causes beyond its control, including earthquakes, fires, floods, strikes or other labor disputes, shortage of labor or materials, accidents to machinery, acts of sabotage, riots, delay in or lack of transportation or the requirements of any government authority.
11. Shipping; Delivery. Unless otherwise expressly agreed in writing by Omron:
    a. Shipments shall be by a carrier selected by Omron; Omron will not drop ship except in "break down" situations.
    b. Such carrier shall act as the agent of Buyer and delivery to such carrier shall constitute delivery to Buyer;
    c. All sales and shipments of Products shall be FOB shipping point (unless otherwise stated in writing by Omron), at which point title and risk of loss shall pass from Omron to Buyer; provided that Omron shall retain a security interest in the Products until the full purchase price is paid;
    d. Delivery and shipping dates are estimates only; and
    e. Omron will package Products as it deems proper for protection against normal handling and extra charges apply to special conditions.
12. Claims. Any claim by Buyer against Omron for shortage or damage to the Products occurring before delivery to the carrier must be presented in writing to Omron within 30 days of receipt of shipment and include the original transportation bill signed by the carrier noting that the carrier received the Products from Omron in the condition claimed.
13. Warranties. (a) Exclusive Warranty. Omron's exclusive warranty is that the Products will be free from defects in materials and workmanship for a period of twelve months from the date of sale by Omron (or such other period expressed in writing by Omron). Omron disclaims all other warranties, express or implied. (b) Limitations. OMRON MAKES NO WARRANTY OR REPRESENTATION, EXPRESS OR IMPLIED, ABOUT NON-INFRINGEMENT, MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE OF THE PRODUCTS. BUYER ACKNOWLEDGES THAT IT ALONE HAS DETERMINED THAT THE PRODUCTS WILL SUITABLY MEET THE REQUIREMENTS OF THEIR INTENDED USE. Omron further disclaims all warranties and responsibility of any type for claims or expenses based on infringement by the Products or otherwise of any intellectual property right. (c) Buyer Remedy. Omron's sole obligation hereunder shall be, at Omron's election, to (i) replace (in the form originally shipped with Buyer responsible for labor charges for removal or replacement thereof) the non-complying Product, (ii) repair the non-complying Product, or (iii) repay or credit Buyer an amount equal to the purchase price of the non-complying Product; provided that in no event shall Omron be responsible for warranty, repair, indemnity or any other claims or expenses regarding the Products unless Omron's analysis confirms that the Products were properly handled, stored, installed and maintained and not subject to contamination, abuse, misuse or inappropriate modification. Return of any Products by Buyer must be approved in writing by Omron before shipment. Omron Companies shall not be liable for the suitability or unsuitability or the results from the use of Products in combination with any electrical or electronic components, circuits, system assemblies or any other materials or substances or environments. Any advice, recommendations or information given orally or in writing, are not to be construed as an amendment or addition to the above warranty. See http://www.omron247.com or contact your Omron representative for published information.
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1. **Please do not turn over the question paper until you are told to do so. Disciplinary action may be taken against you if you do so.**

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3. Please write your Matriculation Number on the front of the answer book.

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