MET 2
MANUFACTURING ENGINEERING TRIPOS PART IIA

Friday 2 May 2025 9:00 to 10:40

Paper 2

MODULE 3P2: OPERATION AND CONTROL OF PRODUCTION MACHINES AND SYSTEMS

Answer two questions, one from each of sections ***A*** *and* ***B.***
Answers to sections ***A*** *and* ***B*** *must appear in separate booklets.*
All questions carry the same number of marks.
The ***approximate*** *percentage of marks allocated to each part of a question is indicated in the right margin.*
Write your candidate number not your name on the cover sheet of each booklet.

STATIONERY REQUIREMENTS
8 page answer booklet x 2
Rough work pad

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Engineering Data Book

10 minutes reading time is allowed for this paper at the start of the exam.
You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.
You may not remove any stationery from the Examination Room.

SECTION A

Answer one question from this section.

Question 1

(a) Describe the key assumptions and limitations of *Merchant's cutting model* when applied to machining processes. Discuss how these assumptions influence the accuracy of the predicted cutting forces and shear plane angle.

[10%]

(b)

(i) Draw the Merchant force diagram for a machining process. Label all forces and angles clearly and describe their physical significance.

[15%]

(ii) Discuss the effect of increasing the rake angle α on the cutting forces, shear angle, and energy efficiency of the machining process.

[10%]

(iii) Show that

$$\tan\phi = \frac{r\cos\alpha}{1 - \mathrm{r}\sin\alpha}$$

Where r is the cutting ratio, α is the rake angle, and ϕ is the shear angle.

[20%]

(c) A manufacturing process involves machining a workpiece using the following conditions:

- Cutting velocity (V): 120 m/min;
- Undeformed chip thickness (t_1): 0.15 mm;
- Deformed chip thickness (t_2): 0.3 mm;
- Cutting force (F_c): 1500 N;
- Thrust force (F_t): 600 N;
- Rake angle (α): 12°.

(i) Calculate the percentage of the total power that is dissipated in the shear plane. Comment on your answer.

[25%]

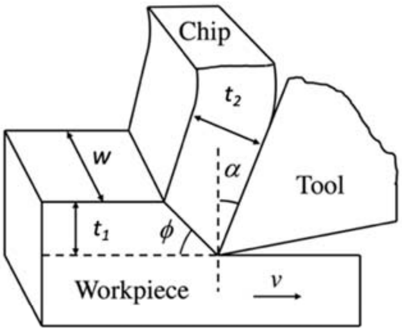
(ii) Calculate the shear plane angle ϕ using Merchant's equation.

$$\emptyset = 45° + \frac{\alpha}{2} - \frac{\beta}{2}$$

Where β is the friction angle. How does this result compare with previous result using the chip ratio method in part b) (iii)? Comment on any discrepancies.

[20%]

Merchant's Cutting Model



t_1 undeformed chip thickness
t_2 deformed chip thickness
α rake angle
ϕ shear angle
v cutting speed
w chip width

Forces in orthogonal cutting

R	Resultant force
F_t	Thrust force
F_c	Cutting force
F	Friction force
N	Normal force
F_s	Shear force
N_s	Normal force to shear plane
β	Friction angle

Forces on the shear plane

$$F_s = F_c \cos\phi - F_t \sin\phi$$
$$N_s = F_t \cos\phi + F_c \sin\phi$$

Forces on the tool-chip interface

$$F = F_c \sin\alpha + F_t \cos\alpha$$
$$N = F_c \cos\alpha - F_t \sin\alpha$$

Merchant's shear angle relationship

$$\emptyset = 45 + \frac{\alpha}{2} - \frac{\beta}{2}$$

(TURN OVER

Question 2

(a)

(i) Briefly explain how a manufacturing company can apply *Statistical Process Control* (SPC) techniques to determine the performance of a machining operation and the benefits it is likely to achieve.

[10%]

(ii) Describe the key stages in applying SPC techniques for such an operation.

[20%]

(b) The company uses a CNC machine tool to produce precision shafts with a target diameter of 50.00 mm. The following information applies:

- The cutting tool has a life of 50 parts under the current machining conditions. Tool wear causes dimensional variation over time;
- Sample size n: 5 parts per sampling interval;
- The process is monitored every 10 parts;
- The tolerances for the shaft diameter: 50.00 ± 0.10 mm;
- Historical process mean: $\mu = 50.01$ mm;
- Standard deviation: $\sigma = 0.03$ mm.

The data presented in Table 1 was collected over 10 samples, 50 parts.

Sample No.	$\bar{X}$ (mm)	R (mm)
1	50.02	0.06
2	50.03	0.05
3	50.01	0.07
4	50.02	0.08
5	50.00	0.06
6	50.01	0.05
7	50.04	0.09
8	50.03	0.04
9	50.02	0.06
10	50.01	0.07

Table 1

(cont.

(i) Plot the $\bar{X}$ and R control charts for this data. Control chart factors for this data set are: Mean Factor $A_2 = 0.577$; Upper Range $D_4 = 2.114$; and Lower Range $D_3 = 0$. Comment on your answer.

[25%]

(ii) Calculate the process capability indices *Cp* and *Cpk*. Interpret the results and decide whether the process is capable of meeting the specifications.

[25%]

(iii) The process engineer is considering replacing the cutting tool after 40 parts instead of the current 50 parts. Replacing the tool reduces the standard deviation σ to 0.02 mm. Tool change increases downtime, leading to a cost increase of 10% per unit. Should the company adopt the new tool replacement strategy? Justify your answer based on both machining performance and cost considerations.

[20%]

(TURN OVER

SECTION B

Answer one question from this section.

Question 3

(a)

(i) Explain what is represented by the *finite state model* of an operation and how this can be used in automation solutions.

[10%]

(ii) What planning steps are required before a state machine for a production operation can be developed?

[10%]

(b) Consider a machine that forms torsion springs - coils with straight "legs" at the ends - as depicted in Fig 1 (a). A schematic side-on view of this machine is shown in Fig 1 (b). The machine has three motor-driven mechanisms:

- Feeder: A rotating wheel that pushes a strand of wire through the machine;
- Coiler: A mechanism that extends towards the wire (as shown in Fig 1 (c)), forming the wire pushing against it into a coil;
- Cutter: A mechanism that extends towards the wire (as shown in Fig 1 (d)), cutting the wire to release the formed spring.

The machine is fitted with three sensors, which detect the length of the front leg, the length of the coil and the length of the back leg, respectively. The inputs from these sensors, as well as the inputs from the sensors and outputs to the actuators of the three mechanisms, are defined in Table 2. Assume that the Feeder is *off* and both the Coiler and Cutter mechanisms are in the retracted position prior to the start button being pressed. Once the start button is pressed, the intended operation of the machine can be described as follows:

- The Feeder switches on to drive the strand of wire through the machine;
- When the specified length of the front leg is detected by the sensor, the Coiler should extend towards the wire while the Feeder remains on;

(cont.

- When the specified length of the coil is detected, the Feeder should stop, and the Coiler should retract;
- The Feeder should drive the wire again until the specified length of the back leg is detected, at which time it should stop;
- The Cutter should then extend to cut the wire and retract;
- The sequence repeats.

(i) Determine the possible states of each of the three mechanisms and identify the allowable composite states for the machine.

[20%]

(ii) Construct a finite state model of the machine. Indicate all state variables, inputs, outputs and state transition requirements. State all assumptions and justify the model that you propose.

[40%]

(iii) The timing of the machine's operations is found to be highly repeatable. As such, instead of the three sensors that detect the length of the spring coil and legs, the torsion spring forming machine could be designed based on timers in a PLC-based control program. Explain how the replacement of the sensors with timers would be reflected in the finite state model constructed in b) (ii).

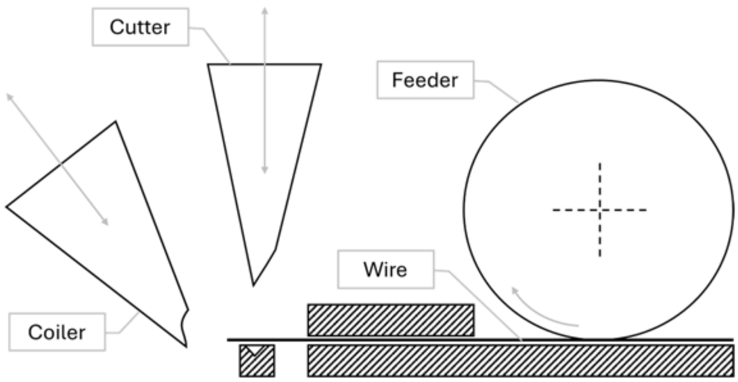
[5%]

(iv) If the timing of the machine's operations is to be controlled by timers in a PLC-based control program, explain how the timers would be integrated in a ladder-logic diagram implementation of the finite state model. (Note: it is not necessary to construct a complete ladder-logic diagram).

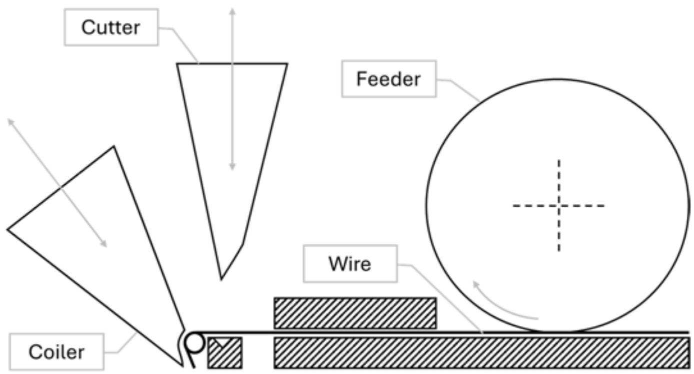
[15%]

(cont.

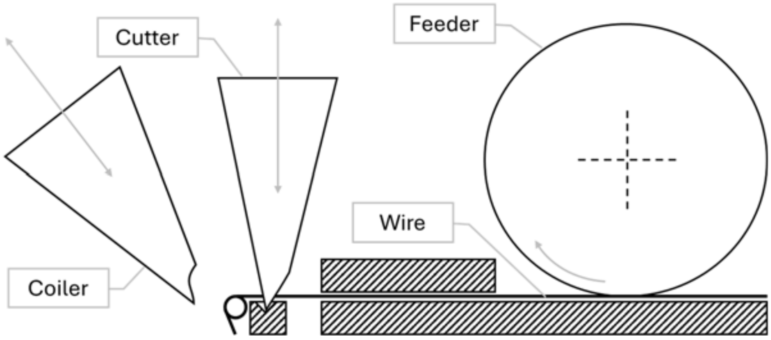
(a)



(b)



(c)



(d)

Fig 1

(a) A torsion spring; (b) A schematic, side-on view of a torsion spring forming machine with both the Coiler and Cutter mechanisms in the retracted position; (c) A schematic view of the machine with the Coiler mechanism in the extended position and Cutter mechanism in the retracted position; (d) A schematic view of the machine with the Coiler mechanism in the retracted position and Cutter mechanism in the extended position.

Inputs		Outputs	
I1	Coiler detected in retracted position	O1	Switches the Feeder motor on
I2	Coiler detected in extended position	O2	Switches the Coiler motor on to retract
I3	Cutter detected in retracted position	O3	Switches the Coiler motor on to extend
I4	Cutter detected in extended position	O4	Switches the Cutter motor on to retract
I5	Specified length of the front leg of the spring detected	O5	Switches the Cutter motor on to extend
I6	Specified length of the coil of the spring detected		
I7	Specified length of the back leg of the spring detected		
I8	Start button pressed		

Table 2

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Question 4

(a) Robots are often used to support material handling in machining cells. Considering anthropomorphic, Cartesian and SCARA robot types, select the most suitable type of robot for each of the following scenarios. In each case, justify your selection.

(i) A manufacturing cell is to handle large, lightweight products that can be loaded into two machines and a buffer in the same orientation.

[15%]

(ii) A manufacturing cell is to handle a high volume of small parts and the machining operations have very short cycle times.

[15%]

(b) In the machining cell of Fig 2, products arrive on the input conveyor and are detected at the end of the conveyor by a sensor. The products first require a machining operation performed by Machine 1 and then a second machining operation performed by Machine 2. After the second machining operation, the products are only unloaded from Machine 2 and placed on the output conveyor if the conveyor has space (as detected by a sensor at the start of the output conveyor). The cell also includes a buffer for products between the two machining operations, which can hold up to eight products.

(i) Draw three Petri Net models that represent the operations of the Robot, Machine 1 and Machine 2, respectively. Clearly label all elements and state any assumptions.

[15%]

(ii) Draw a Petri Net model that represents the overall operations of the machining cell. Clearly label all elements and state any assumptions.

[40%]

(c) Consider that a second robot is added to the machining cell of Fig 2, resulting in the cell layout shown in Fig 3.

(i) Explain the benefits and constraints of making such an addition.

[5%]

(ii) Indicate how the Petri Net model of the single-robot cell's operation developed in b) (ii) should be adapted to represent the operations of the two-robot cell. State all assumptions. (Note: you do not need to draw the complete Petri Net model for the two-robot cell's operation).

[10%]

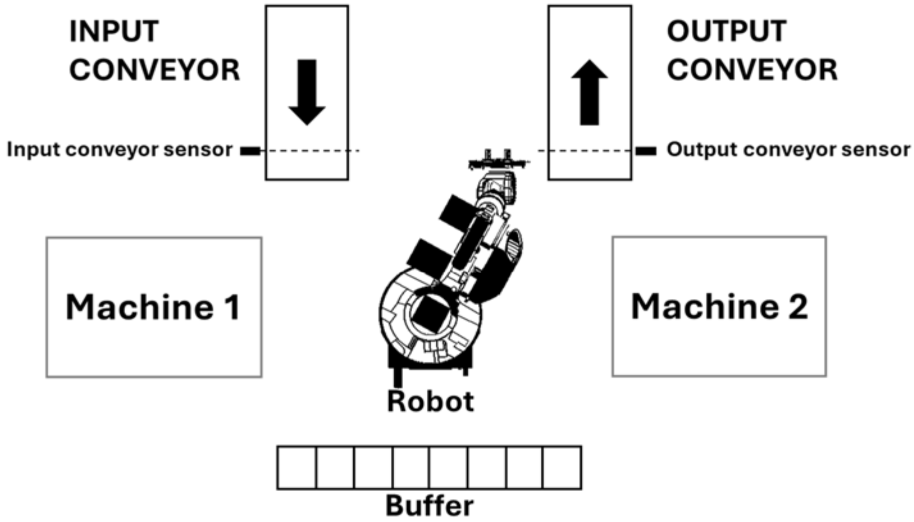

Fig 2

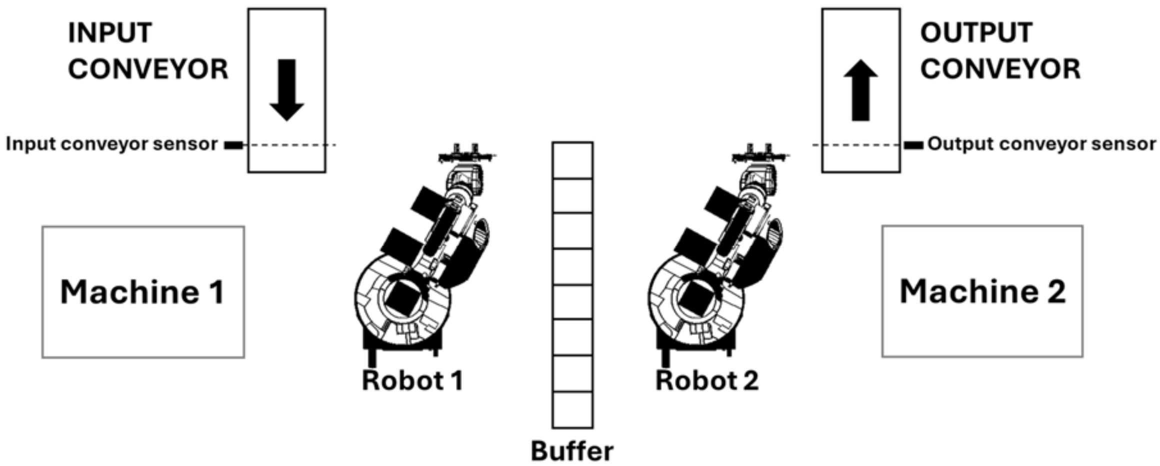

Fig 3

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