MET2
MANUFACTURING ENGINEERING TRIPOS PART IIA

Friday 30 April 2021 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**.*

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.*

STATIONERY REQUIREMENTS
Write on single-sided paper.
You may type your answers.

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed.
You are allowed access to the electronic version of the Engineering Data Books.

10 minutes reading time is allowed for this paper at the start of the exam.

The time taken for scanning/uploading answers is 15 minutes.

Your script is to be uploaded as a single consolidated pdf containing all answers.

SECTION A

1 (a) Describe the basic properties a cutting tool must possess when used in machining operations. [10%]

(b) Explain how Taylor's tool life equation

$$VT^n = C$$

can be used to define the tool wear characteristics of a particular cutting tool/workpiece combination. Here V is cutting speed (m/min), T is tool life (min), n and C are constants. Explain the relevance of the constants n and C. How is Taylor's tool life equation used when performing an economic analysis of a machining operation? [20%]

(c) In a machining experiment, tool life was found to vary as follows. For a cutting speed V = 60 m/min, tool life T = 81 minutes. For a cutting speed V = 90 m/min, tool life T = 36 minutes.

(i) Determine the values of the constants n and C in this case. [20%]

(ii) What is the percentage increase in tool life if speed V is halved? [20%]

(iii) It has been shown that flank wear rate r is proportional to $cot(\gamma)$ where γ is the clearance angle of the tool. Determine the approximate percentage change in tool life if γ changes from 10° to 7°. Comment on your answer. [30%]

2 Metal based additive manufacturing systems are increasingly used for direct part production. *Selective Laser Melting* (SLM) is one such process that can produce parts from a range of metal powders.

(a) (i) Describe the main components of a SLM machine and discuss how they may influence build accuracy. [20%]

(ii) Comment on the general characteristics of *surface roughness*, *tensile strength*, *density*, and *hardness* of parts produced using the SLM process compared to parts machined from bulk materials. [20%]

(b) A company wishes to determine the capabilities of their SLM machine. They build a series of *ten* cubes with targeted dimensions of 10 x 10 x 10 mm. The tolerance on each dimension is ± 0.04 mm. The x, y, and z dimensions of each cube are measured *five* times. Results are given in Table 1, where $\bar{X}$, $\bar{Y}$, and $\bar{Z}$ are the mean dimensions of each part. Xr, Yr, and Zr are the ranges and σ is the standard deviation.

(i) Determine the control limits of the process for each dimension. How can the company make use of this information? Note: Control chart factors are given in Table 2. [20%]

(ii) Calculate the process capability index for each dimension. What do these values tell you about the performance of the machine? [20%]

(iii) In light of your findings, what tolerances would you recommend to the design engineers when designing parts for this production route? Justify your answer. [20%]

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Part	$\bar{X}$	Xr	$\bar{Y}$	Yr	$\bar{Z}$	Zr
1	10.02	0.13	09.95	0.12	09.99	0.05
2	09.97	0.11	09.96	0.13	10.00	0.02
3	10.01	0.13	10.01	0.11	10.01	0.06
4	09.96	0.10	09.95	0.12	10.00	0.03
5	10.03	0.11	10.01	0.10	10.01	0.06
6	09.98	0.09	10.01	0.11	09.99	0.02
7	09.99	0.10	09.95	0.07	09.98	0.07
8	09.94	0.11	09.98	0.04	09.98	0.09
9	09.93	0.13	10.01	0.06	10.01	0.02
10	09.94	0.12	09.95	0.05	09.99	0.06
Mean	09.98	0.11	09.98	0.09	10.00	0.05
σ	0.04	0.01	0.03	0.03	0.01	0.02

Table 1

Sample size n	Mean Factor A_2	Upper Range D_4	Lower Range D_3
2	1.880	3.268	0
3	1.023	2.574	0
4	0.729	2.282	0
5	0.577	2.115	0
6	0.483	2.004	0
7	0.419	1.924	0.076
8	0.373	1.864	0.136
9	0.337	1.816	0.184
10	0.308	1.777	0.223

Table 2

SECTION B

3 (a) Explain what is meant by degrees of freedom (DOFs) in the context of a robot manipulator. How do the differing DOFs affect the operations of *SCARA*, *anthropomorphic* and *delta* robots and the typical applications for each type of robot? [20%]

(b) Figure 1 illustrates a plan view of a simple planar manipulator.

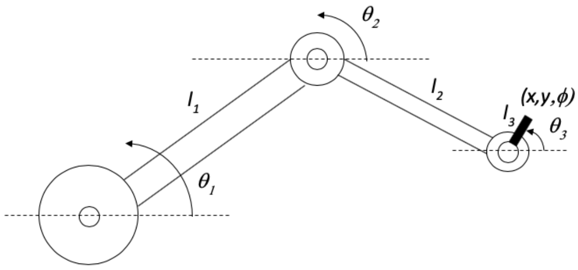

Fig.1

(i) Determine the kinematic mapping between joint angles $(\theta_1, \theta_2, \theta_3)$ and the end effector position (x, y, ϕ) where (l_1, l_2, l_3) refer to the joint lengths. [20%]

(ii) Linearise these equations and hence show that they can be written in a form

$$\begin{bmatrix} dx \\ dy \\ d\phi \end{bmatrix} = M \begin{bmatrix} d\theta_1 \\ d\theta_2 \\ d\theta_3 \end{bmatrix}$$

where dx, dy, and $d\phi$ denotes the linearised version of each of the variables x, y, ϕ and M is a 3x3 matrix. [15%]

(iii) Draw a closed loop diagram for the control of the end effector in which variables (x, y, ϕ) are to be regulated using controllable variables $(\theta_1, \theta_2, \theta_3)$. Make sure you clearly mark all variables and system components in your diagram. [20%]

(iv) How would the selection of point to point control rather than trajectory control affect the control system specified for this manipulator? [10%]

(c) In addition to an effective control system, what is required to enable a robot arm to operate in a fully automated manner? [15%]

4 (a) Buffers are often used in automated production cells to allow parts and work-in-progress (WIP) to accumulate before a downstream operation. Discuss reasons for introducing buffers in an automated production cell. What factors can influence the capacity of buffers? [20%]

(b) Explain what is meant by *deadlock* and how this applies in an automated manufacturing context. [10%]

(c) In a small production cell, a *work-in-progress buffer* is used to store a particular type of sub-component that is used in final assembly. The maximum capacity of this buffer is *four*. A single robot provides sub-components to the buffer from an upstream operation, and the same robot is used to remove sub-components from the buffer for use at the final assembly station.

(i) Describe how this work-in-progress buffer can be represented both as a *finite-state machine* (FSM) model and as a *Petri-Net model*. Use clearly labelled diagrams to illustrate your description. [30%]

(ii) Show under what conditions deadlock could occur in the operation of this system. How could deadlock be avoided? Use diagrams to illustrate your answer. [20%]

(iii) Suggest appropriate ladder logic that could be used to trigger an alarm when the buffer is full assuming the following input and output signals from the ladder:

i1 - robot arrives with part;
i2 - robot removes part;
o1 - set alarm. [20%]

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