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%]

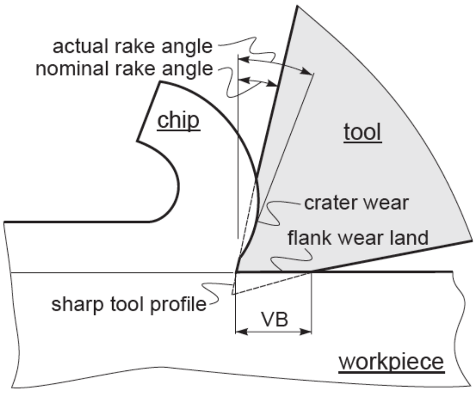
(iii) It has been shown that flank wear rate r is proportional to $cot(\gamma)$ where γ is the clearance angle of the tool. Determine the approximate percentage change in tool life if γ changes from 10° to 7°. Comment on your answer. [30%]

Question 1 Crib:

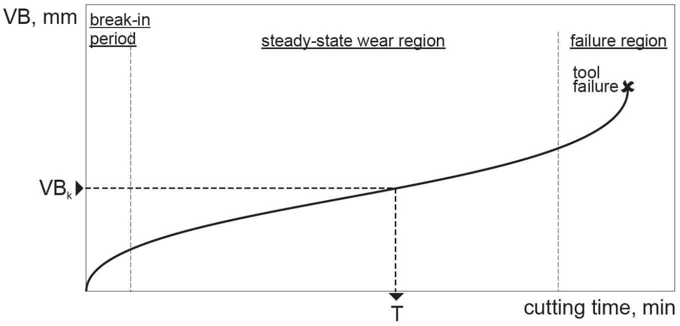
a)

- Tool material must be at least 30 to 50% harder than the work piece material.
- Tool material must have a high hot hardness temperature.
- High toughness
- High wear resistance
- High thermal conductivity
- Lower coefficient of friction

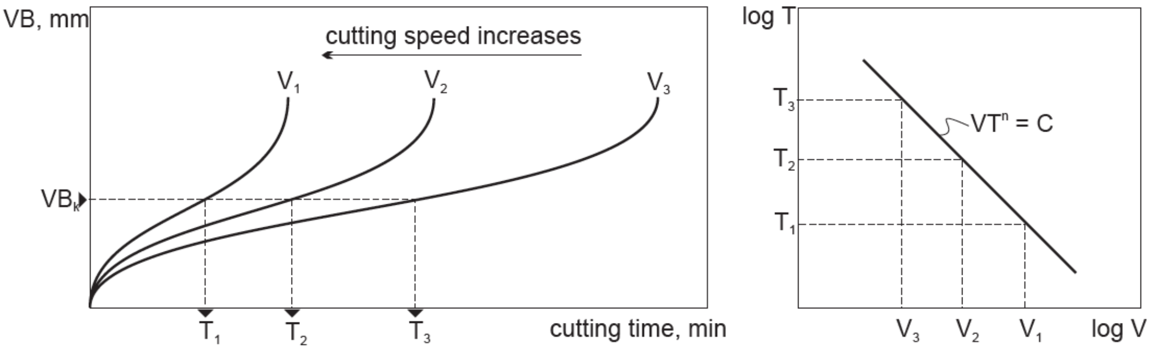
b)



Tool wear is a time dependent process. As cutting proceeds, the amount of tool wear increases gradually. But tool wear must not be allowed to go beyond a certain limit in order to avoid tool failure. The most important wear type from the process point of view is the flank wear, therefore the parameter which has to be controlled is the width of flank wear land, VB. This parameter must not exceed an initially set safe limit. The safe limit is referred to as allowable wear land (wear criterion), VBk. The cutting time required for the cutting tool to develop a flank wear land of width VBk is called tool life, T, a fundamental parameter in machining.

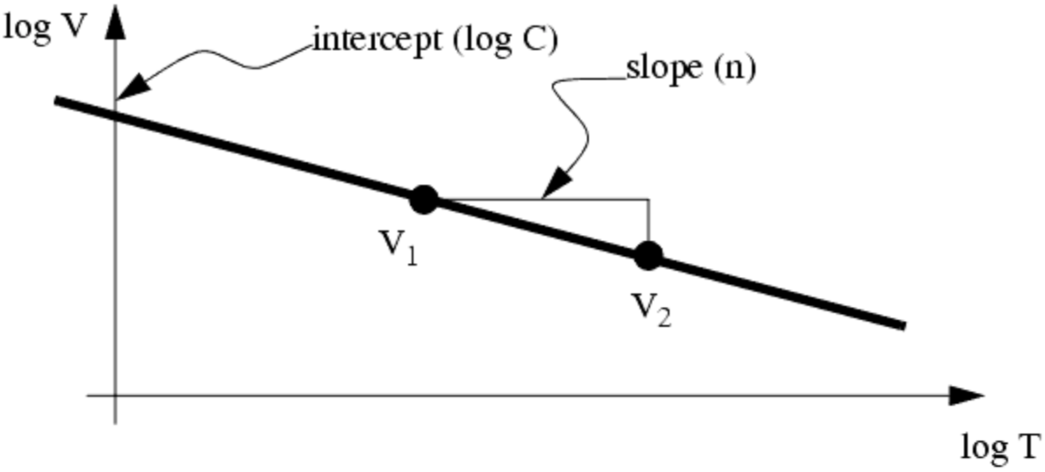


As cutting speed is increased, wear rate increases, so the same wear criterion is reached in less time, i.e. tool life decreases with cutting speed.



If the tool life values for the three wear curves are plotted on a natural log-log graph of cutting speed versus tool life as shown, the resulting relationship is a straight line expressed in an equation form called the Taylor tool life equation: $VT^n = C$. Where n and C are constants. The value of n is relatively constant for a given tool material. Where the value of C depends on tool material, work material and speed whose values depend on cutting conditions, work and tool material properties, and tool geometry. On a Log V -

Log T plot, C is the intercept on the speed axis (the speed for a 1 min tool life), and n is the slope.



Production cost and production rate are critically important for a manufacturing operation. Increasing production rate means producing *more* from the *available* resources. Decreasing production cost means *less* expenditure for the *same* volume of production. If the conditions are so selected to maximize the production rate and minimise the production cost, profit can be maximized. Taylor's tool life equation can be used to calculate the average cost per part, which can then be optimised for production rate or production cost.

c)

i) Taylors tool life equation is given as

$$VT^n = C$$

Where V is cutting speed, T is time, and n and C are constants. We need to find *n* and *C for the conditions of V1 = 60 m/min, T1 = 81 min, and V2 = 90 m/min, T2 = 36 min.*

Taking Taylors too life equation we have

$$\log V1 + n \log T1 = \log C$$

and

$$\log V2 + n \log T2 = \log C$$

where

$$\log V1 + n \log T1 = \log V2 + n \log T2$$

$$\log V1 - \log V2 = n \log T2 - n \log T1$$

$$\log\left(\frac{V1}{V2}\right) = n \log\left(\frac{T2}{T1}\right)$$

Giving

$$n = \frac{\log\left(\frac{V1}{V2}\right)}{\log\left(\frac{T2}{T1}\right)}$$

Note: better students will go straight to this expression from their answer in part c)

From the process conditions we have

$$n = \frac{\log\left(\frac{90}{60}\right)}{\log\left(\frac{36}{81}\right)}$$

$$n = 0.50$$

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For the constant C

$$VT^n = C$$

$$C = V1.T1^n$$

$$C = 60.81^{0.5}$$

$$C = 60x9 = 540$$

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ii) Given Taylors tool life equation

We have

$$V2T2^{0.5} = V1T1^{0.5}$$

Given that

$$V2 = \frac{V1}{2}$$

We have

$$\frac{V1}{2}T2^{0.5} = V1T1^{0.5}$$

$$T2 = 4T1$$

Thus the percentage increase in tool life is

$$= \frac{(4T1 - T1)}{T1} \times 100 = 300\%$$

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iii)

We have two conditions

For T1, $\gamma = 10^0$

For T2, $\gamma = 7^0$

The percentage change in tool life is given by

$$P = \frac{(T2 - T1)}{T1} \times 100$$

Also, note that

$$Tool\ life \propto \frac{1}{flank\ wear\ rate}$$

So

$$T \propto \frac{1}{\cot \gamma}$$

Hence

$$P = \frac{\left(\frac{1}{\cot \gamma_2} - \frac{1}{\cot \gamma_1}\right)}{\frac{1}{\cot \gamma_1}} \times 100$$

$$P = \frac{\tan \gamma_2 - \tan \gamma_1}{\tan \gamma_1} \times 100$$

$$P = \frac{\tan 7^0 - \tan 10^0}{\tan 10^0} \times 100$$

$$P = -30.36\%$$

In this case, the reduction in clearance angle has reduced the tool life by around 30%. Too small a clearance angle will result in intense rubbing and thus poor surface quality and a shorter tool life.

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%]

Table 1

	Dimensions (mm)					
Part	$\bar{X}$	Xr	$\bar{Y}$	Yr	$\bar{Z}$	Zr
1	10.02	0.13	9.95	0.12	9.99	0.05
2	9.97	0.11	9.96	0.13	10.00	0.02
3	10.01	0.13	10.01	0.11	10.01	0.06
4	9.96	0.10	9.95	0.12	10.00	0.03
5	10.03	0.11	10.01	0.10	10.01	0.06
6	9.98	0.09	10.01	0.11	9.99	0.02
7	9.99	0.10	9.95	0.07	9.98	0.07
8	9.94	0.11	9.98	0.04	9.98	0.09
9	9.93	0.13	10.01	0.06	10.01	0.02
10	9.94	0.12	9.95	0.05	9.99	0.06
Mean	9.98	0.11	9.98	0.09	10.00	0.05
Standard Deviation	0.04	0.01	0.03	0.03	0.01	0.02

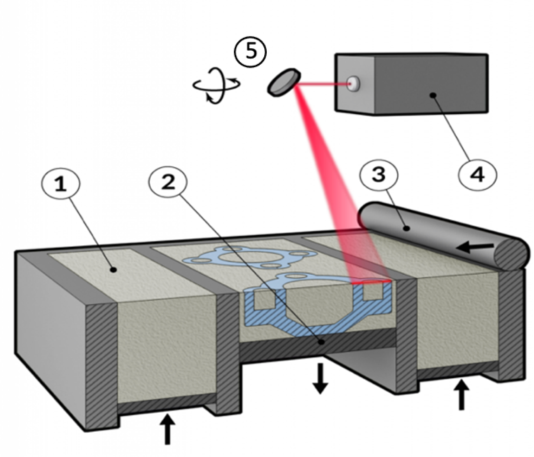
Table 2

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	.729	2.282	0
5	.577	2.115	0
6	.483	2.004	0
7	.419	1.924	0.076
8	.373	1.864	0.136
9	.337	1.816	0.184
10	.308	1.777	0.223

Question 2 Crib.

a) (i)

The main elements of a SLM machine are shown below.



Selective laser melting is an additive production technique which makes 3D printing of metal parts possible. The prerequisite for printing is that the desired material is in fine powder form (1). A thin layer of the metal powder is applied by a spreading roller or blade (3,4) which is then fused by a high-energy laser beam (4) that is scanned across the surface by x-y galvanometer mirrors driven by the 3D data set (5). After one layer has completely melted, the platform is lowered by a set increment (2) and another thin layer of powder applied. When the defined areas are fused, both the new layer and the layer underneath are fused, achieving a bulk compound across the layers. The desired component is thus created layer by layer. When printing is complete, excess powder is removed, leaving the constructed object with a smooth surface that usually requires little or no post-processing.

Build accuracy can be influenced by the performance of all system components.

1) The material must have a well controlled powder size distribution between 20-50μm diameter and spherical morphology to enable consistent melting and ease of handling when each layer is spread. Poor material specifications will lead to high levels of porosity and the risk of failed builds due to delamination.
2) Each layer height is defined by the positional accuracy and repeatability of the build piston. This must be capable of resolving step increments of the order of 5μm. Failure to achieve this will have an impact on the accuracy of the builds in the z-axis.
3) The roller, or levelling blade must be able to sweep across the plane of the build and create a uniform powder layer. Wear and tear on the recoating mechanism will influence the layer thickness and impact the fusion of each laser, the bonding between layers, and the overall dimensions of the part, particularly in the Z axis.
4) The laser and associated beam train have a major influence on machine performance. Variations in laser power, beam diameter and pointing stability all serve to impact on the ability to melt consistently and accurately.
5) The performance of the galvanometer and scanning optics ultimately determine the machine's ability to consolidate each layer in terms of the required melt profile. These

systems are generally very accurate with the ability to deliver scan paths with resolutions on the order of 5 µm. Problems can arise with mirror coatings leading to low reflectivity, heat build up and thermal distortions of the optics.

ii)

Surface Quality: When using thin layers (50µm), and small powders (<25µm diameter). High surface quality can be achieved with surface roughness values approaching 50µm Rz. The use of larger powders reduces the surface quality since the imprint of un-melted powders leaves a witness mark on the outer surface of the part. Machined parts can reach very high surface quality with sub-micron surface roughness levels, particularly with diamond machining.

Tensile Strength: Tensile strength of parts often match those of machined wrought materials. This very much depends on the quality of the build, the amount of interlayer bonding, and the porosity level within the part.

Density: Part density can reach 99.99%, although this is at the very limit of the process. The challenge is delivering uniform melting across the whole part volume. This is no easy task since powder packing in the bed can vary resulting in density variations. The process is quite violent compared to solid state welding. Spatter and vapour explosions lead to trapped voids remaining within the part. This is a problem for many industries looking to apply the technology. Machined components generally have full densities, although this of course is determined by the

Hardness: The hardness of the metals produced in a selective laser melting machine is always higher than those of bulk materials if the parts are not annealed in a post processing step. This is due to the very high solidification rates that can reach millions of degrees per second which result in extremely fine microstructures.

b)

(i)

For the X-chart, control limits are given by

$$UCL = \overline{\overline{X}} + A_2\overline{R}$$
$$LCL = \overline{\overline{X}} - A_2\overline{R}$$

For the R-chart, control limits are given by

$$UCL = D_4\overline{R}$$
$$LCL = D_3\overline{R}$$

Where

$$\overline{R} = \frac{\sum R}{k}$$

$$\overline{R} = mean\ range\ of\ each\ sample$$

$$k = number\ of\ samples$$

$\overline{\overline{X}}$ = the mean of means for each dimension

Is this case, using the data in Table 2 for a sample size of 5, $A_2 = 0.58$, $D_3 = 0$, and $D_4 = 2.115$

Note: some candidates may confuse sample size with sample number, i.e using 10 instead of 5.

Control limits are then calculated as

Control limits	X	X-Range	Y	Y-Range	Z	Z-Range
UCL	10.04	0.24	10.03	0.19	10.02	0.10
LCL	9.91	0.00	9.93	0.00	9.97	0.00

Some candidates may sketch the graphs, although this is not necessary since observations can be made directly from the data in Table.1. This is very useful information for the company. It describes the statistical performance of the machine. It is a measure of random variation and therefore defines the capability of the machine. Once established, control charts can be used to compare future machine performance and identify any degradation or improvement in its operation.

Note: good answers will include a sketch of typical control charts used to monitor the machine performance going forward.

ii)

The process capability index measures how close the process centre is to the nearest specification limit. Its value is determined by the minimum value of

$$C_{pk} = \min \{C_{pkl}, C_{pku}\}$$

with

$$C_{pkl} = \frac{\bar{x} - LSL}{3\sigma_w} \qquad C_{pku} = \frac{USL - \bar{x}}{3\sigma_w}$$

where $\bar{x}$ is the process mean and s_w is the standard deviation.

The following table give the C_{pk} values for each dimension

Capability index	X	Y	Z
C_{pkl}	0.16	0.21	1.02
C_{pku}	0.60	0.71	1.25

Comment:

It is clear that the machine is incapable of delivering the required specification in X and Y dimensions since C_{pk} is equal to 0.16 and 0.21 respectively. The machine is capable of delivering specifications in Z, since C_{Pk} is equal to 1.02. This puts the Z capability in the *OK* category (C_{pk} between 1.0 and 1.33). This is likely due to the fact that the Z dimension is sensitive to layer height which is set by the precision of the build chamber piston. The X and Y dimensions are inaccurate. Part accuracy in X and Y dimensions are usually limited to around 100-150 µm. This is due to the low stability of the lasers, limitations of high-speed optical scanners, the instability in the melt pools, and the beam size variations across the bed (since the beam diameter changes across the bed due to path length variations).

iii) Looking at the performance of the machine it is clear that it is incapable of meeting tolerances of +/- 0.04 mm. If tolerances were relaxed to +/- 0.15 mm, the machine would deliver the following C_{pk} values.

Capability index	X	Y	Z
C_{pkl}	1.20	1.47	4.15
C_{pku}	1.63	1.98	4.37

This puts all dimensions in the *Good* category with the exception of X which is in the *OK* category. I would also recommend that the scanner is checked in the X axis as it may be operating out of specification.

Note: some candidates may give a higher or lower level of process specifications for part dimensions. This is fine as long as they justify their choice.

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.

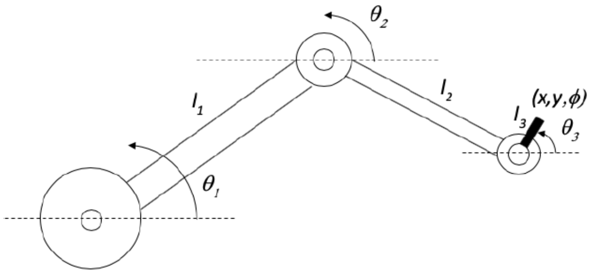


Fig.1

(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%]

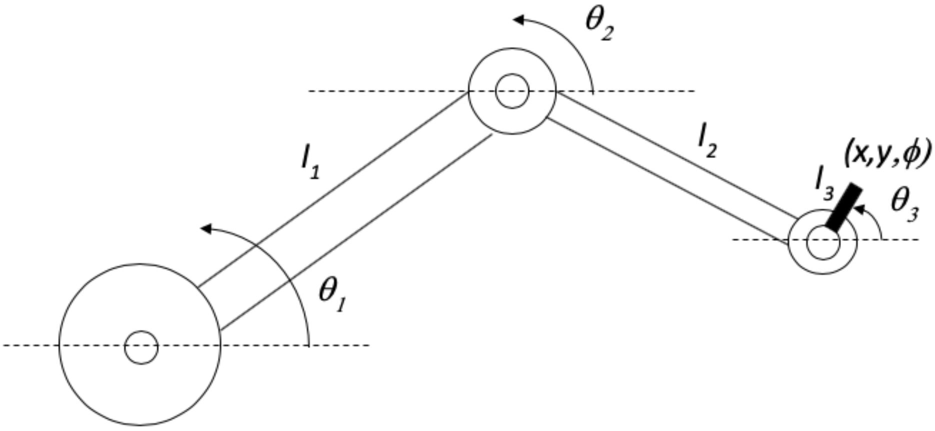
SOLUTIONS

Q3

a) Different robot styles have different degrees of freedom. A robot's degrees of freedom relates to joint configuration. The number of degrees of freedom relates to the number of controllable joint motions within the robot arm. (These motions can be both linear and rotational). The greater the number of joints, the greater the degrees of freedom and the more dextrous (flexible) the robot is.

Robot Type	Degrees of freedom	Application Features	Typical Applications
Cartesian	3	Used for X,Y,Z motions of products and tools. No capability for rotating or skewing the product. (Heavy Payloads & large working volume)	Often used in basic packaging or material loading requiring large work volume
Scara	4	Used for the X,Y,Z motions and rotation B of products and tools. No capability for skewing the product. (Medium Payloads, high speed & high precision)	Often used in high speed electronic assemble operations requiring accuracy
Anthropomorphic	6	Used for the X,Y,Z motions and rotation A,B,C of product and tools. (Wide range of payloads & complex working volume)	Often used in complex assembly and welding applications requiring high levels of dexterity.

b) Fig 1 illustrates a plan view of a simple three axis planar manipulator.



(i) Determine the kinematic mapping between joint angles θ_1, θ_2. θ_3 and the end effector position x, y, ϕ where l_1, l_2. l_3 refers to the joint lengths. [20%]

By inspection of the geometry:

$$\begin{aligned} x &= l_1 \cos\theta_1 + l_2 \cos\theta_2 + l_3 \cos\theta_3 \\ y &= l_1 \sin\theta_1 - l_2 \sin\theta_2 + l_3 \sin\theta_3 \\ \phi &= \theta_1 - \theta_2 + \theta_3 . \end{aligned}$$

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

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

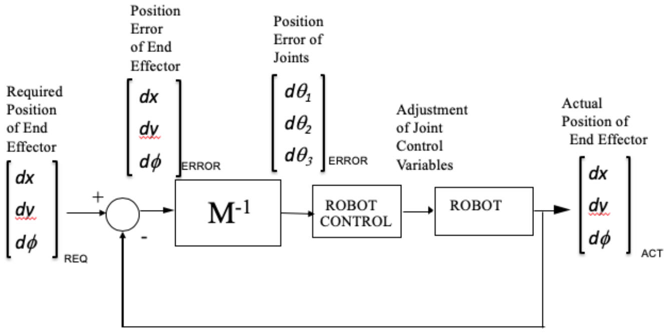
where d denotes the linearised version of each of the variables and M is a 3 x 3 matrix. [20%]

$$\begin{aligned} dx &= -l_1 \sin\theta_1\, d\theta_1 - l_2 \sin\theta_2\, d\theta_2 - l_3 \sin\theta_3\, d\theta_3 \\ dy &= +l_1 \cos\theta_1\, d\theta_1 - l_2 \cos\theta_2\, d\theta_2 + l_3 \cos\theta_3\, d\theta_3 \\ d\phi &= d\theta_1 - d\theta_2 + d\theta_3 \end{aligned}$$

and hence M is given by

$$\begin{bmatrix} -l_1 \sin\theta_1 & -l_2 \sin\theta_2 & -l_3 \sin\theta_3 \\ l_1 \cos\theta_1 & -l_2 \cos\theta_2 & l_3 \cos\theta_3 \\ 1 & -1 & 1 \end{bmatrix}$$

(iii) Hence 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 (θ_1, θ_2. θ_3). Make sure you clearly mark all variables and system components in your diagram [20%]



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

- In terms of the feedback diagram, this choice directly affects the required or reference input and the robot control system which translates errors into adjustment of the joint control variables.
- Point to point control - essentially a request for a single step between two positions allows the control system to select the most appropriate joint variables for that motion.
- Trajectory planning and control is a computationally involved task because it reduces the movement between two positions to a number of step changes (a staircase) and each step requires what is effectively its own point to point control
- In both cases each step represents a sequence of joint configurations and operations which must be compatible with allowable and desirable movements

c) *Suggest ways in which adaptive control could be used to enhance this robotic control system?* *[15%]*

Adaptive control is not directly discussed in the context of robot control but discussed extensively in the context of machine tool control and in lectures the parallel between the two were noted. Hence suggestions for the ways in which adaptive control could be introduced include:

Constrained Adaptive control
- power constrained or force constrained so that robot can operate most safely and economically

Optimised Adaptive Control
- optimisation of speed of manipulator depending on loaded / unloaded conditions and the weight of the load, whether at the beginning / middle / end of trajectory etc

A bonus point for noting that robot operating conditions are generally less variable on a day to day basis

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%]

Q4

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?

- balance of flow between different operations
- allow for " batching of different parts"
- absorb delays, absences, disruptions
- allow for resequencing of items
- provide opportunity for inspection / quality control

Factors influencing buffer capacity
- size of likely timing / flow mismatches
- space available
- cost of holding inventory

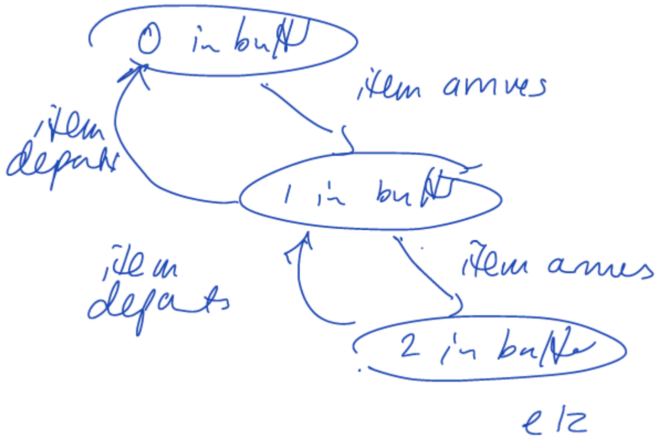
b) Explain what is meant by notion of deadlock and how this applies in an automated manufacturing context.

Deadlock is a circular state in which each operation is waiting on the completion of another operation which is in turn cannot be completed until the original operation is completed. In an automated production context it generally refers to the availability of a particular resource (Resource A) being dependent on the availability of another resource (Resource B) and vice versa.

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.

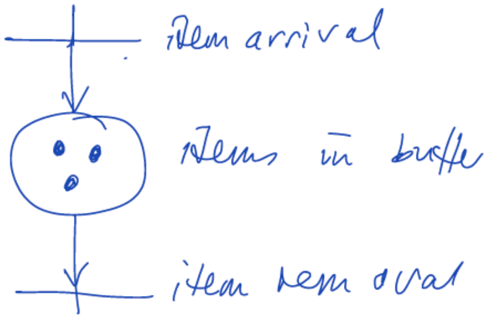
i) Describe how this work-in-progress buffer can be represented both as a finite-state machine (FSM) model and as a Petri-Net model. Use clearly labelled diagrams to illustrate your description.

i) In a FSM the four sub-component buffer needs to be represented as a separate states, each corresponding to one of the possible numbers of items in the buffer (i.e. 5 possibilities - 0,1,2,3,4). The movement between each of these states is driven by either the arrival or removal of sub-components from the buffer. A possible candidate FSM is given in the diagram although many possibilities exist

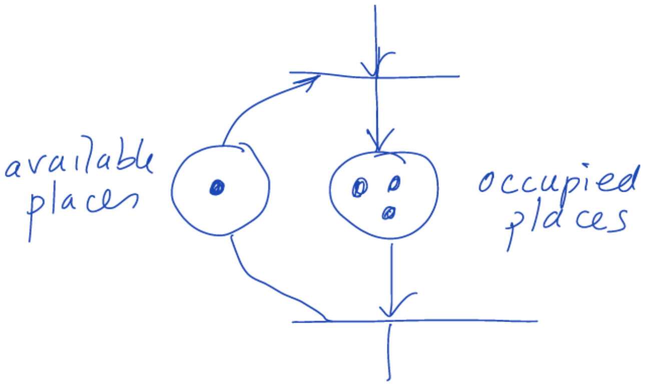


The maximum size of the buffer is explicitly represented in the case of the FSM by the (finite) number of states indicated in the diagram - although this is not sufficient to control the system such that it doesn't exceed the capacity

In a Petri Net, a more compact representation can be achieved with tokens being used to mark a single place with the required number of sub-components in the buffer.

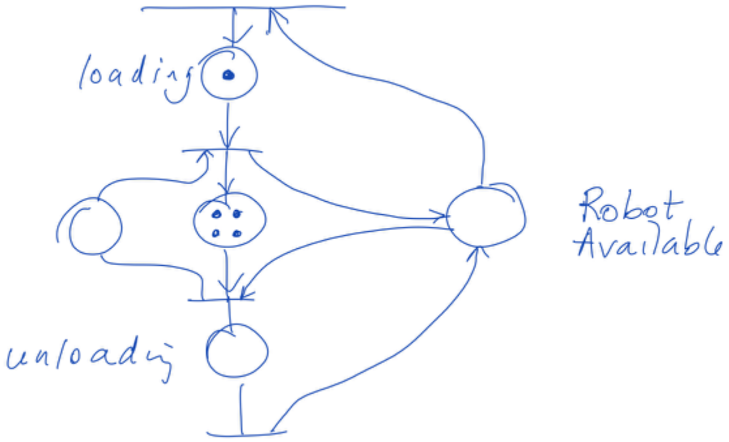


In the Petri Net the maximum size of the buffer can be represented by the introduction of an additional place whose tokens represent the (current) number of available places for sub-components in the buffer. i.e. The total number of tokens in the original place and this additional place sum to the buffer capacity (four).



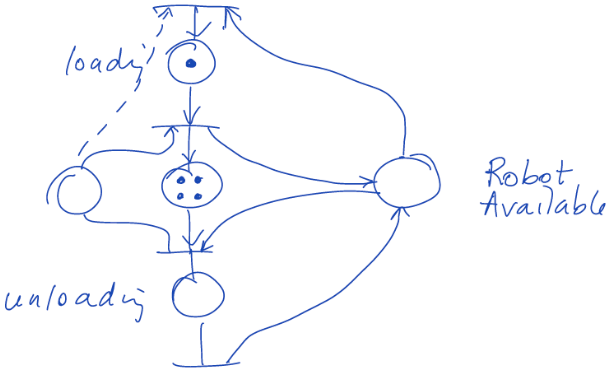
ii) Show under what conditions deadlock could occur in the operation of this system? How could deadlock be avoided? Make use of appropriate diagrams to illustrate.

ii) Deadlock could occur in the logic for this buffer system if - for example - the robot collects a part for loading into the buffer while the buffer is already full. This can be represented by the diagram below



Deadlock can be avoided in a number of ways

- by not permitting loading to start if there is no buffer space available (as per the dotted line in the diagram below)



- by ensuring unloading is always prirotised over loading. This could be achieved for example by the use of an inhibitor arc.
- using independent loading and unloading resources.

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

This can be addressed in a number of ways. An important point to note is that the PN to ladder logic conversion approach described in the lectures is not immediately applicable because it is illustrated only for situations where there is a maximum of one token possible per PN place.

Hence the students may suggest a number of ways to do this:

- directly writing ladder logic
- making use of the finite state machine
- adapting the petri net (it will become more complex as a result)

The essence of the resulting code will be that
- a separate internal variable will be required for each location in the buffer
- these variables need to be used to generate a part count for the buffer
- a counter introduced in lectures can't be directly used as there is no method for reducing the count
- the alarm will be triggered only when all of the internal variables are set to be ON