3P2 2015 Section A

Q-1 Crib

Part a)

i) **Statistical Process Control**. If a product is to meet or exceed customer requirements, it should be produced by a process that is stable or repeatable, i.e it should be produced with little variability around a target dimension or quality characteristic. Statistical Process Control or SPC is a collection of problem solving tools useful in achieving manufacturing process stability through the reduction of variability.

Chance causes of variation are those that are produced by phenomena constantly active within a system that have predictable variation. They are said to be 'in control'

Assignable causes of variation are produced by new, unanticipated, emergent or previously neglected phenomena within the system. This variation is inherently unpredictable and is said to be 'out of control'

ii)

1. Control charts are a proven technique for improving productivity. A successful control chart program will reduce scrap and re-work.
2. Control charts are effective in defect prevention. The control chart helps to keep the process in control delivering a 'right first time' philosophy
3. Control charts prevent unnecessary process adjustment. Adjusting processes based on tests unrelated to control charts, will often lead to an overreaction to the background noise of the process.
4. Control charts provide background information. Frequently, the pattern of points will contain information of diagnostic value to an experienced operator.
5. Control charts provide information about process capability. It provides information about the value of important parameters and their stability.

Part b) The operator needs to know if the process meets the part specification by performing a capability study. In this case the machining operation is designed to establish particular dimension of the part, lets say diameter, and control limits need to be determined.

If a process is in control, one could expect the control limits to be approximately 75% of the tolerance, centered within the tolerance band.

- The process should be set-up for turning with a suitable tool material and standard process parameters for the tool-material combination.
- The operator should decide how to measure the parts and how frequently these measurements need to be taken.
- Metrology. A measurement technique needs to be chosen that can measure the resulting part diameters to the level of precision required. This could be a direct contact gauge or a non-contact optical gauge. Given that in our case, the diameter is of interest, and is being processed with a high level of precision, there are a number of variations that can occur when taking these measurements. The diameter will vary both around the part and along the part, care needs to be taken to

measure at a point along the part which is consistent from part to part, i.e avoid areas that are likely to taper such as at the end of the part, and to measure a number of diameters around the part in order to gain better insight into the process. One could also use this data to determine the level of roundness through determining the Range of the data.

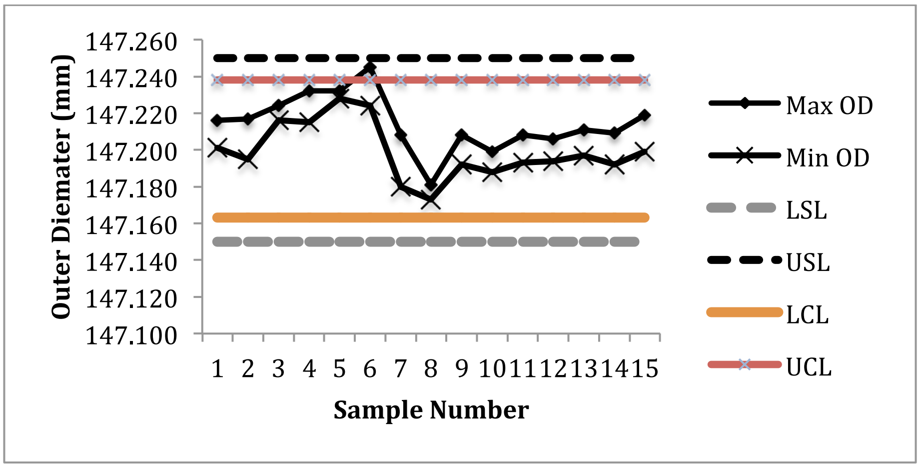
- The operator should run the process to produce a large number of parts. Diameter data should be collected, with the mean and standard deviation determined.
- The mean and standard deviation can be used to determine the UCL and LCL limits (the limits that define variation due to natural causes).
- We now have a view of the limits of the machines normal capability, and can collect then plot data on the control chart to observe the process performance with time.
- If the measured data drifts outside of the control limits, we have part variations due to assignable causes, and action must be taken to correct the process (perhaps due to tool wear or machine variation).
- This acquisition and plotting process should continue at timed intervals throughout the production operation, taking a sample from time to time. The frequency of sampling can be altered if part variation is seen to increase, or decrease.

c)
i) Sketch a control chart for this operation.

In this case the USL and LSL are found to be
LSL = 147.15, and USL = 147.250

The average diameter of the population is (147.207 mm), standard deviation (0.0151), giving UCL (147.25) and LCL (147.16) over a 6 sigma spread.

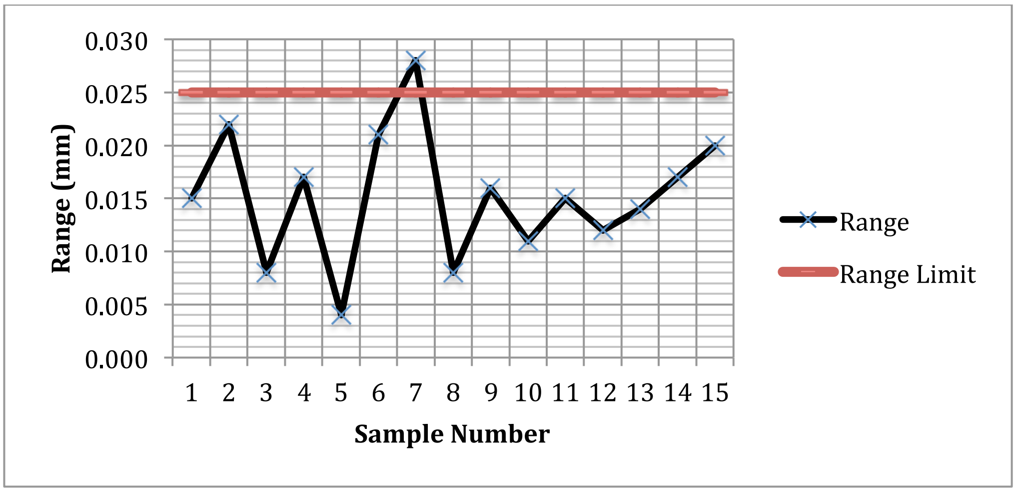
The Control chart is shown below.



ii) The chart gives considerable information on the process and the part. If the process is 'in control' the OD should sit within the UCL/LCL/LSL/USL limits. The data gives feedback on current conditions within the process and information on rates of change. The data also gives assurance (or not) that the process is performing to the requirements of the customer. It is an early warning system that is used to great effect across a number of process operations.

Rates of change of data is important when interpreting Control Charts. There might be some fluctuation in data at the beginning as the machine warms up. That is a special cause that cannot be removed, but needs to be considered. It is a strong indicator of tool wear. In this case the measured values are moving move towards the UCL in the later part of shift-1, operator A has adjusted the process at the end of the shift, by changing his tool offsets, making the process move towards the LCL. Operator B can also see the process move back towards the UCL as the tool wears once more. Once two cycles have been measured, the operator will have a good idea of how the 'machine system' is performing. The slope of the data is a measure of the rate of tool wear, and can be used to determine tool change intervals in order to avoid the expense of catastrophic failure. In addition, the operators can always be sure that they are producing to specification and have the process under control.

iii) The Range is actually a measure of the effective roundness of the parts. Since this will give trends in roundness variation. One could set a measure of acceptable roundness by stating that the limit of roundness be 25% of the tolerance on diameter (the operators choice in this case rather than statistically determined). Hence the upper control limit of the range, R, becomes 0.025. Plotting the range data with these limits is shown below. One can see that samples go out of acceptable roundness with sample 7, just after the machine has its tool offsets adjusted. The parts come back into full specification after that point and sit well within the range of acceptable roundness values. *Good Answers will develop this approach, with most candidates choosing to simply describe the Range of the data being related to roundness.*



iv) The Cp index describes process capability; it is the number of times the spread of the process fits into the tolerance width. The higher the value of Cp, the better the process. It can be determined by C_p = (USL-LSL)/(UCL-LCL) = 0.1/(147.25-147.16) = 0.1/0.09 = 1.11 (the process is just about in control).

Note: A “good” value for C_p of 1.33 equates to the UCL and LCL which sit at 75% of the spec limits, in this case, UCL= 147.238 and LCL = 147.163.

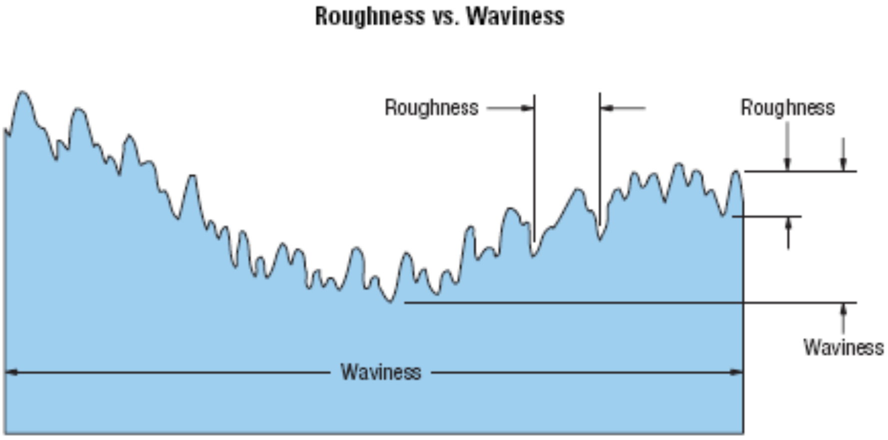
Examiner Summary:
Number of Answers: 14
Average: 64%
Part a) was comprehensively answered by nearly all candidates showing that they had a good grasp of the collection of problem solving tools that make up SPC analysis
Part b) was less well answered with lower performing candidates simply choosing to state the most basic aspects of control charts without mentioning the link between Control Charts and the process control options that it provides the operator. High scoring candidates gave a clear “process

operator" perspective of the steps taken to establish a control chart for a turning operation, rather than a generic list of statistical operations. .
Part c) – produced mixed responses with candidates showing some grasp of the statistical methods but lacking precision in their analysis.

Q-2 CRIB

a)

Surface roughness or texture is the measure of the finer surface irregularities in the surface and is composed of two main components: roughness; and waviness (form). These are the result of the manufacturing process employed to create the surface.



The ability of a machining operation to produce a specific surface roughness depends on many factors. For example, in end mill cutting, the final surface depends on the rotational speed of the end mill cutter, the velocity of the traverse, the rate of feed, the amount and type of lubrication at the point of cutting, and the mechanical properties of the piece being machined. A small change in any of the above factors can have a significant effect on the surface produced.

Waviness is most often the result of small fluctuations in process conditions such as changing distances between the cutting tool and the surface of the workpiece. These fluctuations may be caused by cutting tool wear or worn machine bearings, both of which generate unbalanced conditions, chatter, vibration and instability in the machining setup. It is important to eliminate sources of imprecision in machine tools in order to improve surface finish and form. Modem day machine tool manufacturers are able to achieve surface accuracies in the range of Rz 50 nm mm on account of improved machine designs and advanced cutting tool materials technology such as diamonds and CBN.

The problem of erroneous movement that leads to roughness and waviness is very difficult to eliminate completely. Despite attempts to create optimised machine designs, there is a limit to the accuracy and surface finish that could be achieved. Errors induced by thermal deformation of the machine structure, cutting force deformation, or tool wear etc., cannot be completely eliminated by detailed machine designs. Even with the advent of ceramic materials technology within modern machine spindles and machine beds, these approaches are still subject to changes that occur in the process or in the machine shop environment on a day to day basis.

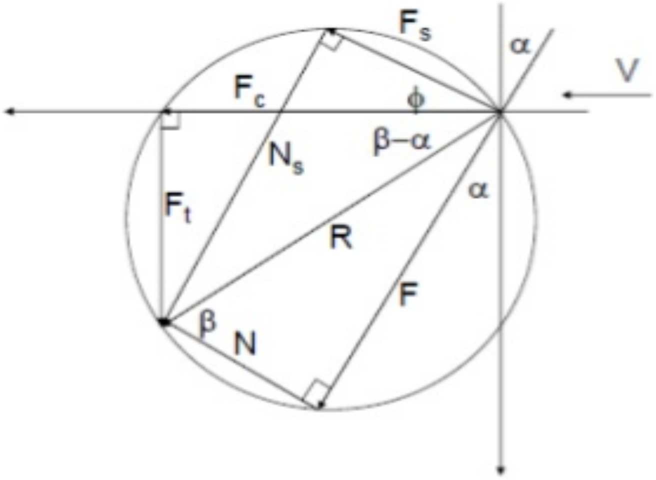
b)

Cutting forces can be directly measured with the use of an in-process force sensor or dynamometer, or indirectly measured from the use of currents drawn by servo motors within the machine tool. The error compensation system monitors the condition of the machine continuously and any error that may be generated is compensated for accordingly during the machining operation in order to effect greater control of surface finish and form.

Cutting force is the most sensitive indicator of machining performance. It determines the requirements of the machining system to induce shearing along the cutting direction. It depends on the tool geometry, tool material, process settings such as rake angle, and coolant level. Cutting force can have both static and dynamic components depending on the stability of the process settings which are determined by the stability of the machine settings. One way to improve surface finish and form is the technique of error compensation. This technique enables the manufacturer to deliver more accurate machine tools as well as the creation of components with higher precision. Error compensation allows the traditional inaccuracies of machining operations to be overcome. Errors induced as a result of the cutting force variation due to the cutting action, caused either by excessive deformation at the tool/workpiece interface, or excessive deformation of the machine tool structure, lead to increased surface roughness or errors in the surface form (waviness) of the workpiece. Measurement of cutting forces during machining allows the machine to compensate for the errors caused by cutting force variations.

C)

i) Set up the problem as follows using Merchant's force circle



ii)

We know that $P_{total} = F_C \times V_C$ = 500N x 2m/s = 1000 W
and $P_{shear} = F_s \times V_s$

where from the force circle
$F_s = RCos(\emptyset + \beta - \alpha)$

and
$R = \sqrt{F_c^2 + F_t^2}$ = 538 N

We therefore need to determine ϕ and β

The cutting ratio r is given by

$r = {}^{t_o}/_{t_c}$ = 0.15/0.2 = 0.75

and $\phi = tan^{-1}\frac{r\cos\alpha}{1-r\,sin\alpha}$ = 42^0

Given that $F_c = RCos(\beta - \alpha), \beta = Cos^{-1}\left(\frac{F_c}{R}\right) + \alpha = 36.7^0$

$$F_s = RCos(\emptyset + \beta - \alpha) = 238\ N$$

P_{shear} = F_s x V_s = 238 x 2.17 = 516 W

% of total power in the shear zone is 516/1000 = 0.516 or 51.6%

Assuming all other parameters supplied remain constant, an increase in rake angle, α, will only affect ϕ in the equation for Fs. Which has the following effects:

$$F_s = RCos\left(\emptyset + Cos^{-1}\left(\frac{F_c}{R}\right)\right)$$

and hence we need only explore the relationship $\phi = tan^{-1}\frac{r\cos\alpha}{1-r\,sin\alpha}$. Students might do this by differentiation or by making a 10% increase in α. A decrease in α will increase the power in the shear zone since it will decrease shear angle and increase shear zone area.

iii) This effect is most likely caused by mechanically of thermally induced changes to the machine structure which results in a displacement of the tool/work piece interface by 50 microns; the scale of the observed waviness.

This will have a significant effect on the process conditions in the following way:

The waviness will directly affect the depth of cut by some 30%

- This will change the cutting ratio, r, where $r = {}^{t_o}/_{t_c}$
- in turn will influence the shear angle, ϕ, $\phi = tan^{-1}\frac{r\cos\alpha}{1-r\,sin\alpha}$
- the % of power used in the shearing process via $F_s = RCos\left(\emptyset + Cos^{-1}\left(\frac{F_c}{R}\right)\right)$

A decrease in shear angle will increase the shear plane area and hence the power dissipated in the shear zone.

NB: It is not possible to calculate the full effect since the un-deformed chip thickness is not known, nor is the cutting force variation or thrust force variation. The cutting forces and thrust forces are likely to oscillate considerably, which could develop resonances in the machine structure, further exacerbating the deviations in surface form. The effect can be minimized by reducing the cut depth or cut speed, since these have the greatest influence on heat generation through a reduction in the friction coefficient at the tool chip interface.

Examiner Summary:
Number of Answers: 22
Average: 65%
Part a) was comprehensively answered by nearly all candidates showing that they had a good grasp of surface roughness (texture) and could distinguish between waviness and roughness.
Part b) was less well answered with lower performing candidates unable to develop the link between cutting force variation and surface roughness/form, often simply choosing to state that machining parameters have an influence without detailing why. Many answers only offered one

method of force measurement, mainly dynamometers, but very few detailed the use of other signals such as servo motor current levels, and the ability to apply error compensation schemes to minimize surface variation.

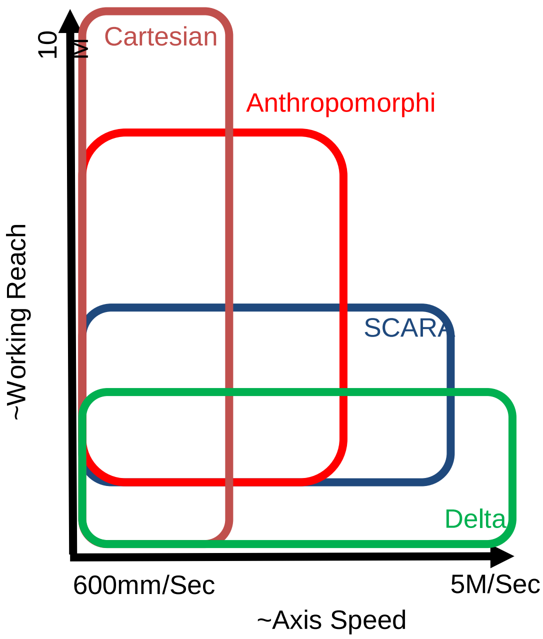
Part c) i) On the whole many candidates returned comprehensive answers to part i) with marks being lost for poor diagrams lacking in detail or annotations. Part ii) proved troublesome for around half of the class, with many answers failing to spot the route forward and exhibiting a level of unfamiliarity with the connections between the various forces. Few answers attempted the latter part of ii), but those that did scored highly. In part c) iii) very few answers delivered with sufficient detail

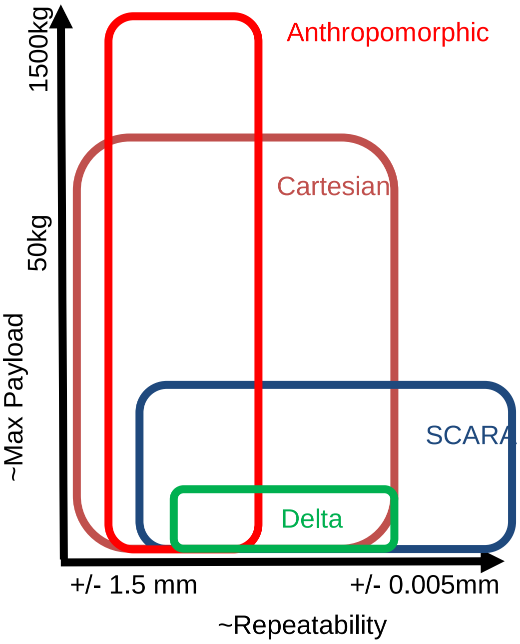
Q3.

a) For this question students will refer to the different metrics for robot operation and performance discussed in lectures such as:

a) Working Volume
b) Payload
c) Speed
d) Resolution
e) Accuracy
f) Repeatability

The diagram below provides ample material for a sensible response to this question.





From these charts SCARA has the edge in terms of axis speed and repeatability but is weaker in terms of reach and load management. Hence it is often used for high precision, high speed assembly of very small parts – e.g. electronics and small mechanical devices.

Note that as its name implies SCARA robots are selectively compliant – they have quite reasonable compliance in X, Y directions but significant vertical rigidity.

(b)

(i)

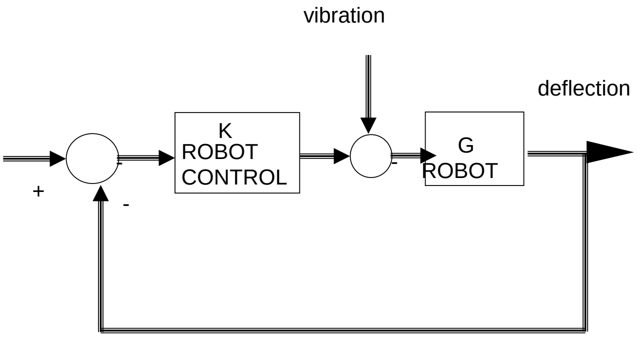
This is a second order system.
The student might
- determine the gain analytically
- sketch a Bode plot and estimate the gain
- use the mechanics data book (simplest)

Using the mechanics data book it is possible to read directly that for a 75 rad/sec disturbance, this system (with damping factor 0.3 and natural frequency 100rad/sec) will have a gain of 1.3 x 0.1 =0.13 mm/kN. This could also be determined from the complex number at w=75rad/sec

Hence for a 0.077kN vibration, the amplitude of the resulting deflection is 0.077 x 0.13 = 0.01 mm. This is just at the acceptable 10um accuracy. It also means that any further disturbances or errors in modelling might lead to unacceptable accuracy levels.

(ii)

The resulting closed loop system is as below



and the closed system from vibration to deflection is given by

$$\frac{G(jw)}{1+kG(jw)} = \frac{0.1{w_n}^2}{-w^2+2cw_n wj+{w_n}^2(1+0.1k)}$$

(iii) The open loop steady state gain is 0.1, and at steady-state w=0, the closed loop reduces to

$$\frac{G(j0)}{1+kG(j0)} = \frac{0.1w_n^2}{w_n^2(1+0.1k)} = \frac{0.1}{(1+0.1k)}$$

Hence, setting k=10 will reduce the open loop gain at steady state by a factor 2.

The proportional controller increases the natural frequency of the closed loop system to $w_n^2(1+0.1k)$ so the higher the value of *k* used the higher the natural frequency and conversely the lower the level of damping – hence oscillations might be expected. A derivative control term in the controller would address this problem.

Examiners Summary

Number of Answers: 14
Average: 65%

The question related to the general properties and feedback control applications of industrial robots. It was well answered overall although there was some significant variability across the different sections.

The first section comparing SCARA and anthropomorphic robots yielded a wide range of responses. Most students understood the basic differences between these two robot types but there was a significant range of quality of responses when asked to compare specific performance characteristics and applications.

The second section looked specifically at the position control of a SCARA robot in the face of disturbances. The first part of this section required the students to estimate the level of impact from a disturbance on the position control loop and to determine whether the impact was within allowable tolerances. This was generally very well done and some allowances were made for variations in the calculation of the impact. The second part of the section then asked the students to consider a feedback control loop and to draw a diagram depicting the position control problem. Some diagrams were rather rough and the closed loop transfer function was often only determined in general terms rather than for this specific case. Many good attempts were made at the estimation of controller magnitude in the final part although fewer students fully understood the implications of the introduction of k on the closed loop damping.

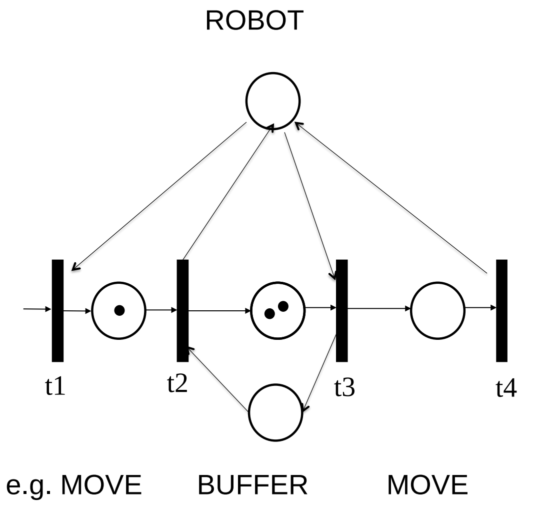
Q4

a)

(i) Deadlock represents a condition where the automated system reaches a state that it cannot move on from. This is generally due to a loop in which the requirements for the commencement of one section of the loop are conditional on the completion of another section which cannot in fact proceed before the first section has been executed.

Deadlock is clearly undesirable because it leads to the "freezing" of the automated process until some form of manual intervention clears the loop.

(ii) The petri net in the diagram provides one example of this situation.



In this diagram transition t1 has just fired and the robot is in use loading the part to the buffer. But the two part buffer already has two parts in place and cannot accommodate a third part and hence t2 cannot fire. Similarly transition t3 cannot fire because the robot is required to do the unloading move so the process is deadlocked.

The petri net can be simply adjusted by shifting the arc from the buffer currently pointing at t2 to make it point to transition t1. Hence the robot cannot commence the move of parts to the buffer unless there is a free space.

b)

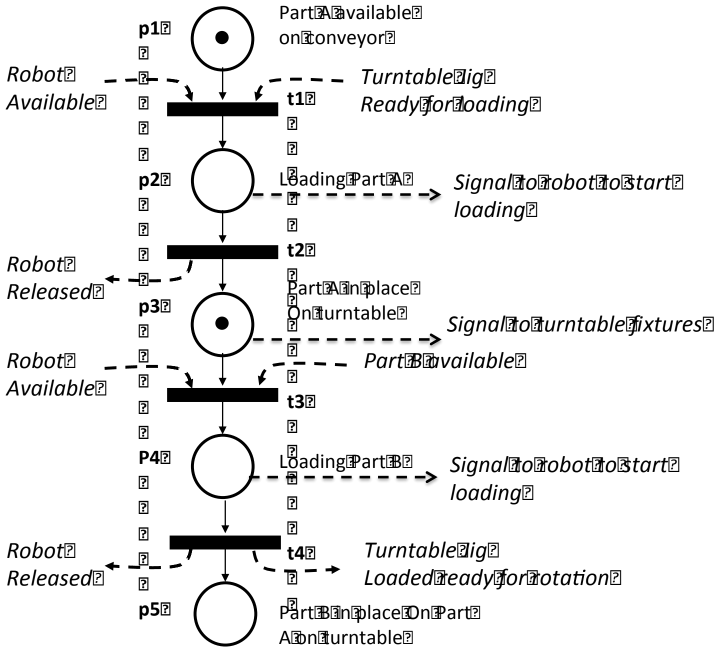
i)

Good responses will at least cover the following points discussed in lectures

- Interfacing to the Physical Systems: making sure that input / output signals to physical environment are in place. Ensure that appropriate communications / handshaking are in place to support error free automation.
- Checking the logic of the cell control design: ensure no deadlock, unreachable states, continuous loops etc.
- Additional Logic for Continuous Operations: ensure system has homing capability
- Generating PLC code from Petri Nets: follow procedure to convert PN to appropriate code such as Ladder Logic.

ii)

Students would be expected to supplement the petri net provided to include signals to and from the robot and the turntable. A simple diagram, in line with procedures taught in lectures is as below.

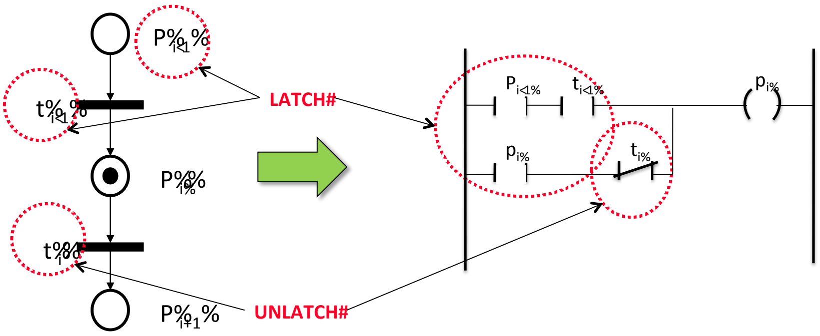


Additionally handshaking procedures should be considered to ensure error safe operation of the system. This would involve – for example – introducing an additional place between p1 and p2 in which the additional transition is triggered by the robot confirming that it has embarked on the loading process.

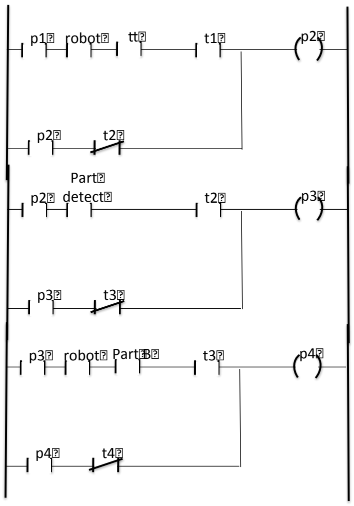
Further, an initialisation routline could be added to ensure the system is starting its sequence with
- turntable empty in both locations
- robot in home position
- conveyor loading buffer empty

Depending on the overall process and the degree to which the operations run in continuous mode there are many variations on this.

(iii) Following the general conversion procedure discussed in lectures along the lines of



it is possible to generate ladder logic of the following form



Note that there are numerous variations.

Examiners Summary

Number of Answers: 22
Average: 61%

This question related to the use of petri nets in the development of automated production operations.

Section a) – requiring students to discuss problems linked to deadlock – was reasonably well attempted. Most students demonstrated a rough knowledge of the deadlock condition though some candidates confused this property with other related – though different - automation system challenges such as concurrency. Fewer students were able to clearly describe a deadlocked process using a petri net diagram. But many achieved partial marks by capturing some aspects of a deadlocked system.

Section b) was based around the design of automation logic for an assembly cell. In part i) most students were able to suggest some of the key steps required to adapt a basic petri net for use in automation and very good responses covered all aspects of the process and used examples to describe the issue. The adaption of the incomplete loading petri net was generally very well done. In addition to adding additional features to the base petri net of the loading operation some students also added further operational steps to their petri net beyond the loading stage which was impressive if a little time consuming.

In Section b) part iii) the students were required to convert the petri net completed in section b) ii) to ladder logic code. Although there was little description given of the approaches used . most candidates were able to produce a basic set of rungs and good students managed to ensure that the transitions in the petri net were adequately matched to latches in the ladder code.