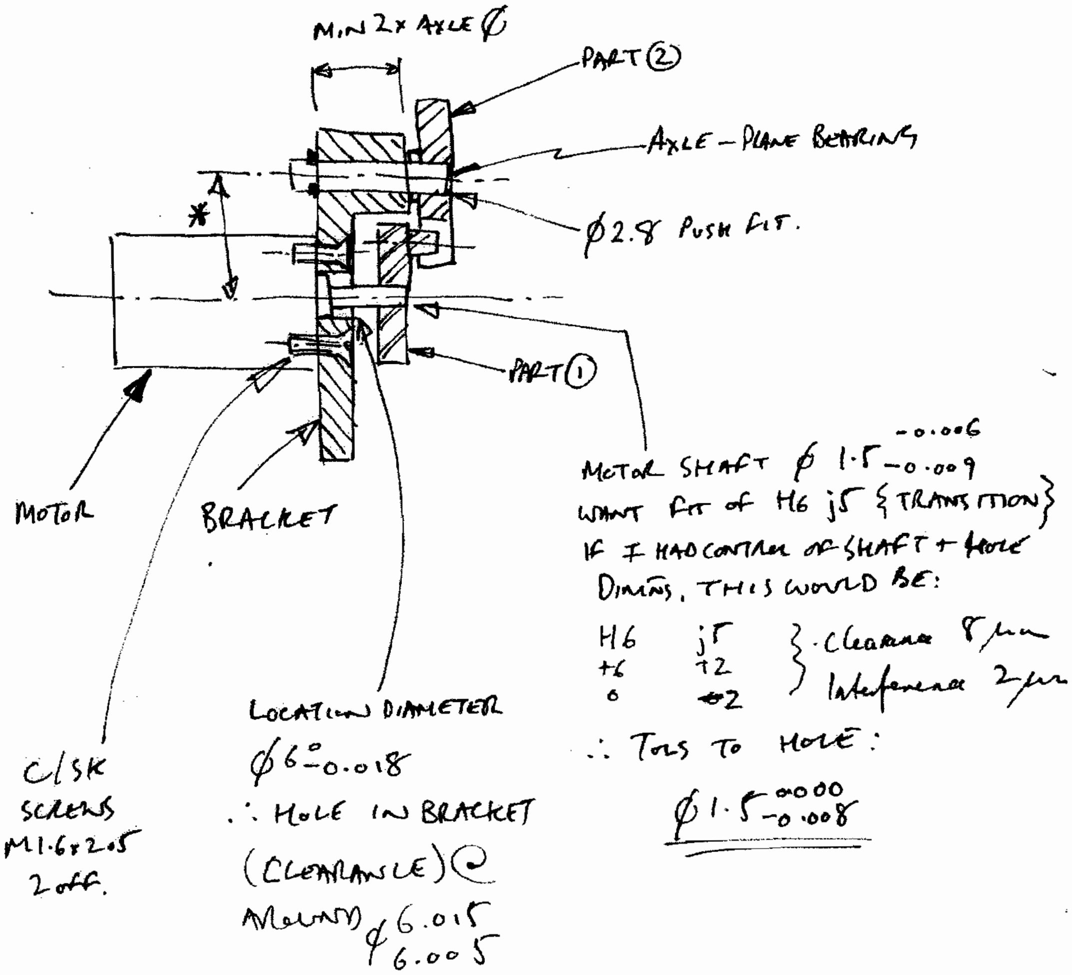
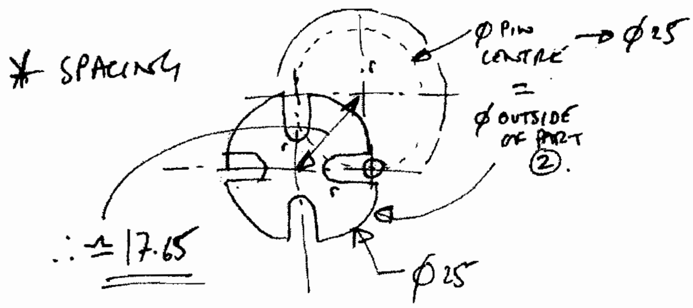
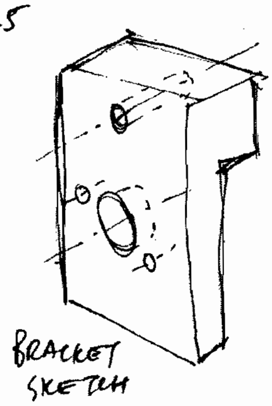
MANUFACTGURING ENGINEERING TRIPOS II
MET1 Paper 1 2007-8
Crib
Examiner: Dr James Moultrie

SECTION A: **Question 1**

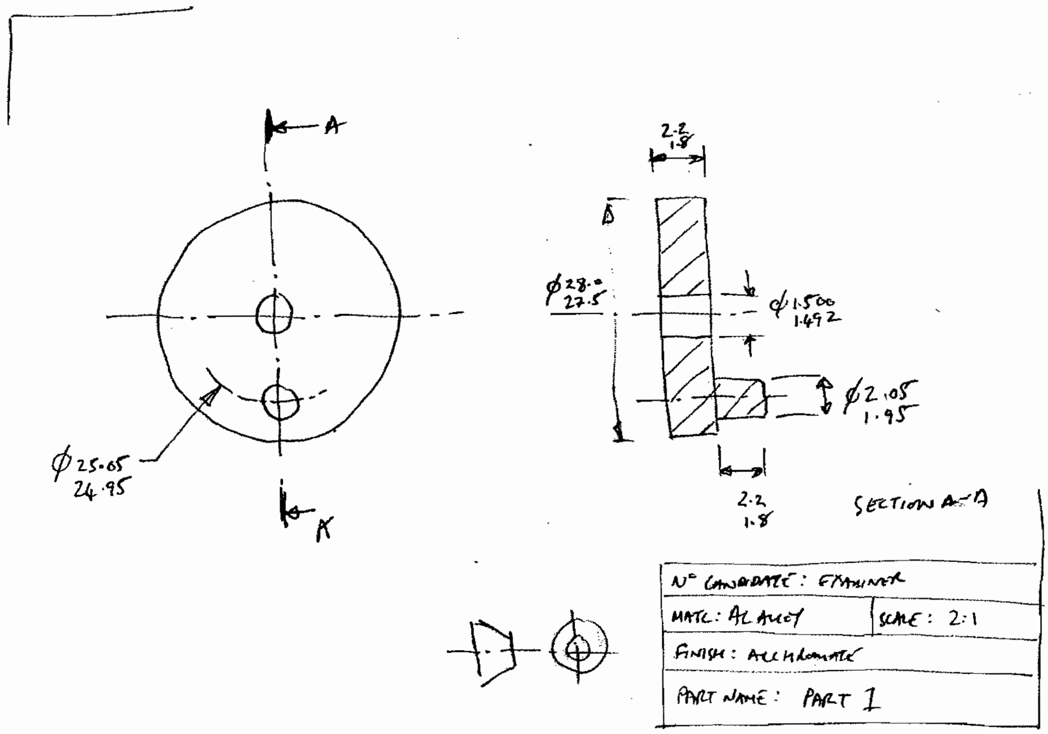
a) A potential design for the holding of these components is shown in the annotated illustration below

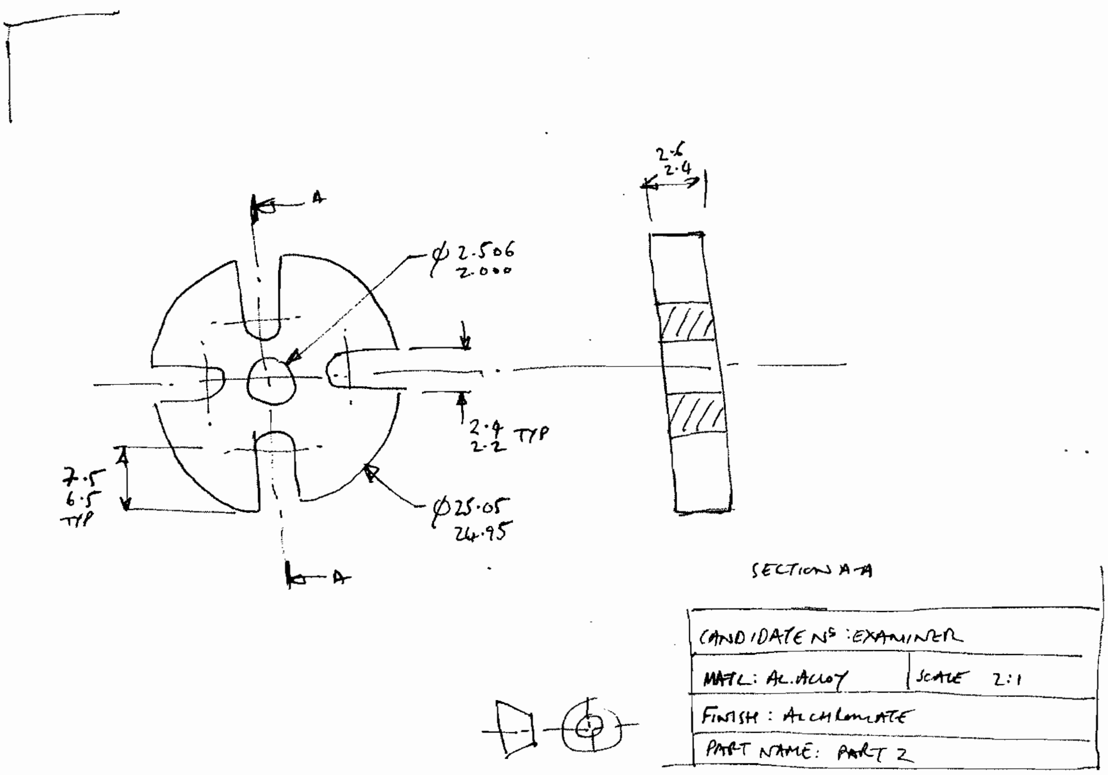






b) With the solution in part (a) in mind, below are the design of two potential components. Specific attention should be given to the 'fit' of the part to the motor shaft and also to the pin in the slot. Marks would be awarded for the precision and clarity of the engineering drawings.





Very few students attempted this question

--------------End of crib for question 1 --------------

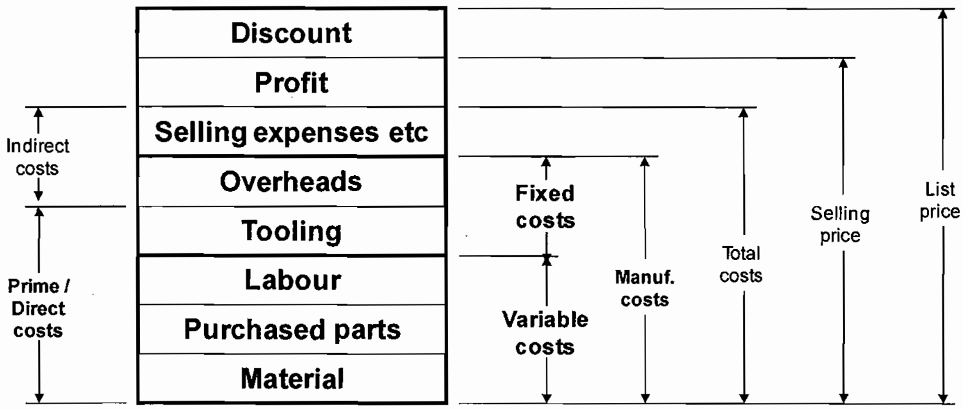
SECTION A: **Question 2**

a) The relationship between unit cost and selling price is shown in the figure below. Unit cost is comprised of fixed costs (e.g. tooling and overheads etc) and variable costs. The variable costs increase in proportion to the number of products produced.

The total product costs however should also include the spend needed to sell the product – e.g. salesmen, promotions etc. Any profits therefore are after all of the costs have been incurred.

If the business sells through a third party (stores, distributers etc), then the list price will also include an allowance for discounting (maybe over several levels).

The design team needs to be aware of all of these costs and set targets for the costs which it directly influences (e.g. materials, tooling, purchased parts, some overheads – and also in some cases selling expenses), based on the profits that the business needs to make. The design team must also understand how their decisions influence these costs over the duration of the design project.



Value is unrelated to either price or cost. A customer's perceived value is derived from the benefits that they receive. Successful products are perceived as having significantly higher value than the manufacturing cost might suggest. Examples could include – ipod etc.

Many students failed to understand the difference between price and value. Better answers included illustrative examples.

b) A new manufactured part is a part that is made to an original design, from either raw material – or a modification to a standard or purchased part. It can either be made in house or subcontract.

If it is subcontract, then the cost can be estimated by sourcing quotations from suppliers. Quotations should include estimates for various production volumes – and also an indication of any up front tooling costs. In addition, the costs to the business of dealing with the supplier need to be considered – and how the quality of manufacture will be ensured.

If the part is to be manufactured in-house, then unit cost will be:

Unit Cost = raw materials + tooling + processing

Where:

Raw matl. = (mass of part + scrap allowance) x (cost per unit mass)

Tooling = design and fabrication of cutters, molds, dies, fixtures etc

The life of the tooling needs to be taken into account ... typically, the tooling cost is amortised over the number of parts to be made per tool (Tooling cost per part = tooling cost / parts per tool)

Processing = labour (rate x hours) + overhead

The overhead is normally charged at a cost driver, that apportions the overall resources to specific types of activity. Other issues that might also need to be considered are - Batch size and also set-up & change-over costs for all processes.

Thus, to minimise costs, the designers should aim to ... Open up tolerances; Reduce number of processes and set-up changes; Choose appropriate materials; Eliminate finishing processes; Choose 'net-shape' processes (moulding, fabrication, forging, extrusion) that provides shapes close to final geometry and also minimises the machining to critical faces only; Use standardised parts and processes; Benefit from other's economies of scale (e.g. modify standard parts)

c) See analysis graph and calculations below.

Need to calculate USL and LSL.

Need to calculate spread for each and plot a mean graph. Useful to calculate process control limits.

It is evident that the process is neither accurate nor precise. Steve maintains a reasonable mean value, but with a very wide spread – thus, he is relatively accurate, but the production is not precise. In contrast, Terry is precise, with a low spread, but not accurate, with an inconsistent mean value.

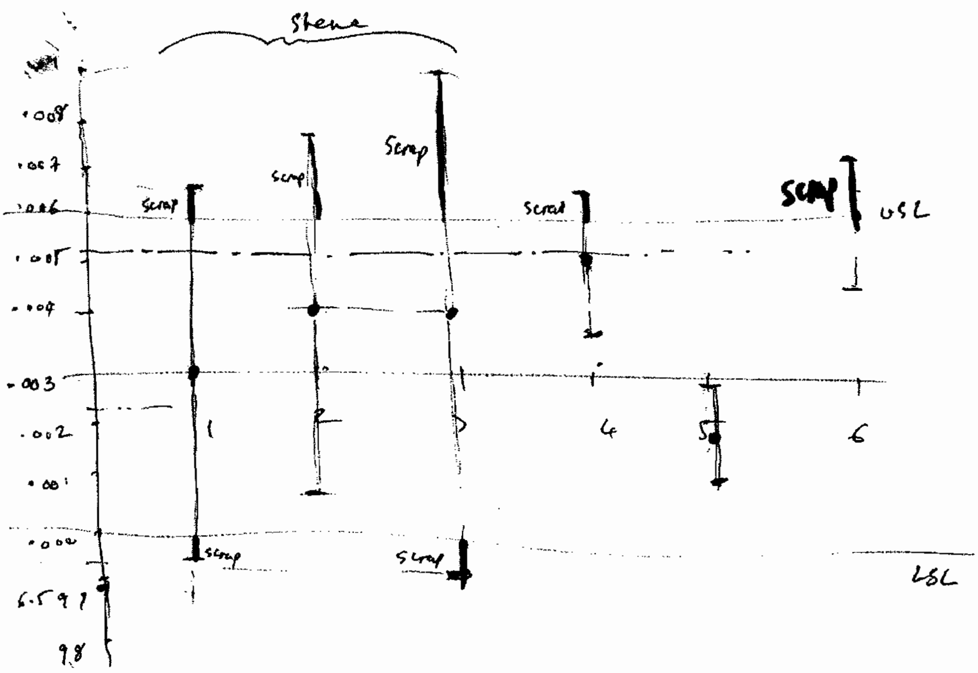
This is reflected in the chart, with the net result that there is a lot of scrap, from both operators.

Offset errors are typically symptomatic of poor set-up. Spread errors are due to variations in process during machining.

It looks as though it might not be possible to achieve both accuracy and precision together. However, it may be possible to learn from both operators, especially Terry, to identify what is being done differently – and why Terry is so much more precise in his work. There are two other options. The first is to open the tolerances on the component – to around 6.01-5.90. This would probably be not desirable. The next option is to determine whether the scrap is due to how the operators are working or are more fundamentally due to the physical capabilities of the machine tool. In the latter case, the recommendation would be to source a more precise machine.

USL	6.008	6.008	6.008	6.008	6.008	6.008
LSL	6	6	6	6	6	6
	Steve			Terry		
	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5	Batch 6
Standard deviation	0.0012	0.0013	0.0015	0.0005	0.0002	0.0005
Mean	6.003	6.004	6.004	6.005	6.002	6.006
3s	0.0036	0.0039	0.0045	0.0015	0.0006	0.0015
	6.0066	6.0079	6.0085	6.0065	6.0026	6.0075
	5.9994	6.0001	5.9995	6.0035	6.0014	6.0045
(USL-m)/3s	1.389	1.026	0.889	2.000	10.000	1.333
(m-LSL)/3s	0.833	1.026	0.889	3.333	3.333	4.000
Min	**0.833**	**1.026**	**0.889**	**2.000**	**3.333**	**1.333**

Upper control limit = 6.0052, lower = 6.0028. Thus, process isn't really capable.



In general, students calculated CpK well. Few students calculated the UCL and LCL, and only few plotted the control chart. Reasoning for improvements was generally limited. Many students stated that Terry was too precise – and that this would cost too much. In practice, whilst he is more precise, it would probably not cost too much.

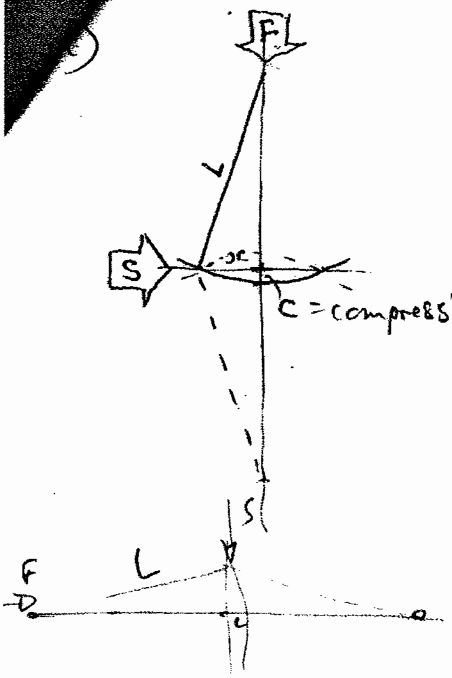
d) Flat datum surface – 0.8RA. This falls between the capabilities of both milling and surface grinding. It is close to the most precise capability of end milling or horizontal milling. Milling would be cheaper than grinding, as one less production process is necessary. However, as a datum surface, even if the surface finish is achievable, the likely recommendation would be to grind the surface. Grinding will produce a surface finish in the range 0.1-1.6 RA.

This was a popular question, in general answered well. The comparison between the two production operators was generally well done. The most common errors were in the last section, where many students failed to suggest appropriate processes for a flat surface.

--------------End of crib for question 2 --------------

SECTION B: **Question 3**

a) Please see working below:



From the trigonometry relationship for small angles, the amount the leg is compressed (c) as it goes from just touching to vertical is given by

$$2Lc = x^2$$

$$\therefore c = \frac{x^2}{2L}$$

and the compressive stress gives

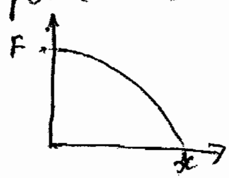
$$\frac{c}{L} = \varepsilon = \frac{\sigma}{E} = \frac{F}{AE}$$

$$\therefore F = AE\frac{c}{L} = \frac{AE}{2}\frac{x^2}{L^2} \quad (1)$$

Consider an interim position where the lateral displacement is a fraction (y) of x. $(0 \le y \le 1)$ Then the incremental axial force still to come $(F_{(R)})$ is

$$F_{(R)} = \frac{AE}{2}\frac{x^2 y^2}{L^2}$$

So the force already present is

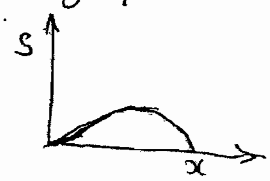


$$F_{(y)} = F - F_{(R)}$$

$$= \frac{AEx^2}{2L^2}(1 - y^2) \quad (2)$$

The sideways force S has to balance forces from 2 legs.

so



$$S = \frac{2AE}{2}\frac{x^2}{L^2}\frac{yx}{L}(1 - y^2)$$

$$= \frac{AEx^3}{L^3}y(1 - y^2) \quad (3)$$

This is a maximum when the slope is zero so differentiate.

$$0 = \frac{AEx^3}{L^3}(1 - 3y^2)$$

$$\therefore y = 0.577$$

and $S_{MAX} = \frac{AEx^3}{L^3}(0.3849) = 0.77\,F\,\frac{x}{L}$

b) Degrees of freedom explained below:

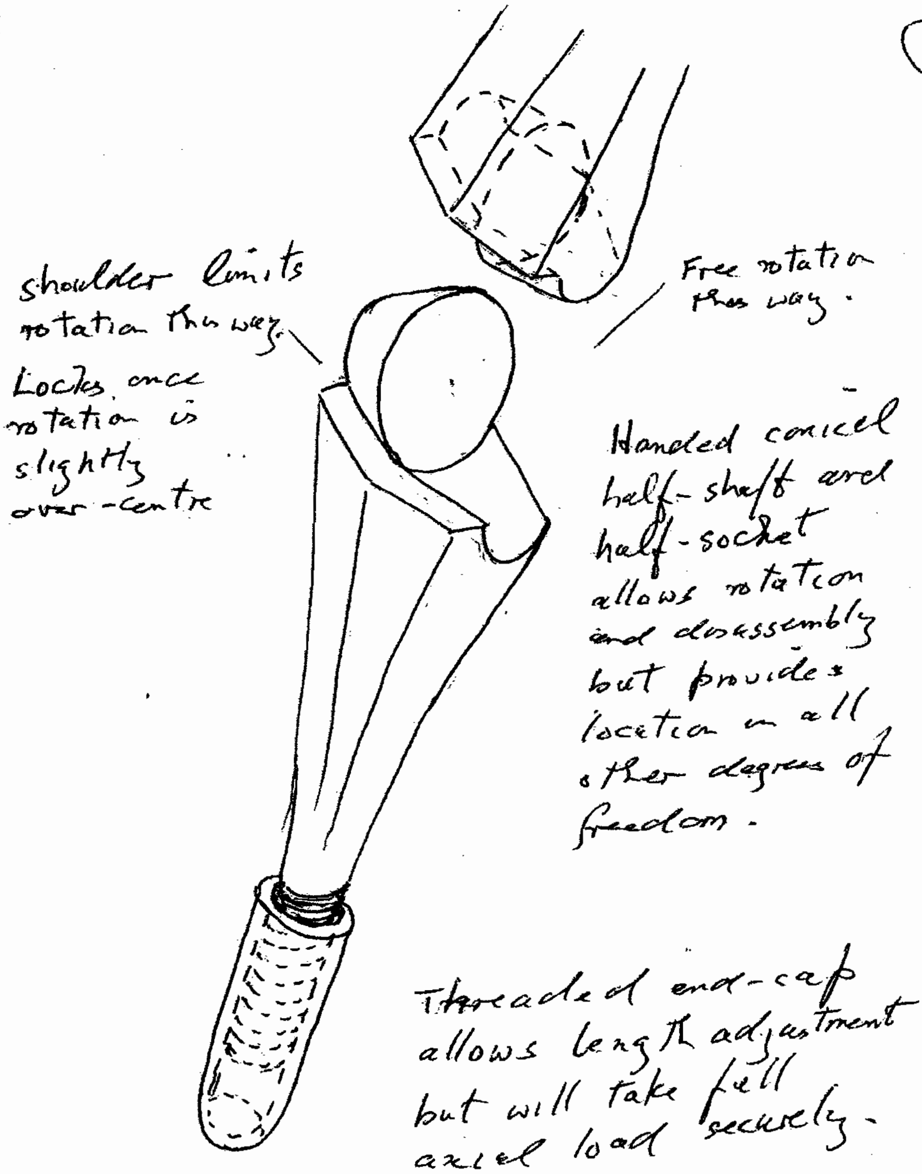
Consider the central joint between the two rods, which creates the mechanism. If the mechanism is in the x-y plane then:-

- There needs to be rotation about the z axis
  - only a small angle from straight one way (perhaps one or two degrees) up to a stop.
  - a reasonably large angle the other way from straight, say 30° or more.
- Between the two rods there wants to be no relative rotation about either the x or y axes.
- In the longitudinal direction (x axis, say) the two rods need to press together firmly in compression and constrain each other, but need to be able to move freely apart, to separate the two rods.
- There must be no relative translatory movement along the other two axes (y, z)

Consider the adjustable rod end on each rod. Relative to the rod:-

- This needs to be able to be moved axially (x direction, say) over a range of adjustment, and also fixed in a chosen position.
- There must be no relative translation or rotation about the other two axes (y, z)
- It may rotate about the longitudinal (x) axis relative to the rod.

c) A possible embodiment is shown below:



Very few students attempted this question.

--------------End of crib for question 3 --------------

SECTION B: **Question 4**

a) Begin by selecting a small number (say 4) of what you consider might be the most important variables. Do not try to track too many at the same time. Allow each factor to vary over what you consider might be a significant range and select say three levels of that factor for the purposes of monitoring.

Note, monitoring two levels will give a simple trend, but monitoring three levels can show a trend and also a curve, and possibly indicate a maximum or a minimum.

It is inefficient to try to do 'scientific' experiments, varying only one factor at once. It is possible to run fewer numbers of experiments, if the factors are controlled to vary in a particular way, such that: in the total number of experiments, each level of a factor occurs the same number of times, so that in the overall average result, the effects of the different levels is neutralised.

The levels for each factor are then varied, each in a different way, through the experiments, such that if the results for all the tests, with one factor at a particular level are selected and arranged, all the other factors will experience their different levels in an equal number of times and so will have a neutral effect.

The difference between this average result and the overall average itself thus shows the effect of that one factor being at that one level. In this way, the effects of all factors at all their levels can be found. Tests like this are called Taguchi Experiments.

These experiments will give trends for these factors across these three levels.

Two refinements are possible. Firstly, it might show that the trend suggests even better results outside of the explored range, or a possible better result somewhere between the measured points. Another set of trials can be done, refining and extending the range of levels used. Secondly, these parameters can be set to their best settings and then experiments can begin which vary another set of factors which are also thought to have an effect and want to be explored.

b) (i) The working for this section is summarised below:

)

If the average of the first three tests is taken, it isolates the effect of the moisture content being at its lowest level of 3%, viz:

30.00
31.25
28.75
Av. 30.00 GPa

Following this through, it would suggest

Moisture content (%)		3	6	9
		30.00	26.90	25.0167
Thickness	(mm)	1	1.5	2
		28.767	27.5167	25.633
Location		Lower	Middle	Upper
		26.267	28.133	27.5167
Age (years)		3	4	5
		26.883	27.5767	27.5167

This suggests that the best properties will come from 3% moisture, 1mm thickness, the middle of the height and at least 4 years old.
Average value is then (30.00 + 28.767 + 28.133 + 27.517)/4
= 28.619 GPa. ✓

b) (ii) The working for this section is summarised below:

c) The selection to get the best properties only uses bamboo from the middle third of the stem and cuts it down to 1mm thickness. To use all the stem and 2mm thickness would give 6 times the yield. It can still be cut at 4 years as there is a regular crop each year from the same land. The young growth is between the old growth, so it is thinnings. All of it can be dried to 3% moisture content. (3)

Using the whole of the stem gives an average

26.267
28.133
27.5167
Av. 27.306 GPa.

Using the above combination gives

30.006
25.633
27.306
27.517
Average 27.614 GPa. – a 35% drop in stiffness for 6x increase in yield.

This was a popular question. The final section caused greatest difficulty, and was generally answered poorly. Students generally failed to consider the ways in which the bamboo utilisation could be optimised, by taking whole stems.

--------------End of crib for question 4 --------------

SECTION C: **Question 5**

a) Time study

Definition: Time study is a technique for measuring the times and rates of working for the elements of a specified job, and for analysing the data to establish the time necessary for carrying out the job at a defined level of performance.

Specific points to be expanded on ...

- **Specified job:** The job must have been subjected to method study first and the details of the process specified eg equipment used, jigs, tools, speeds & feeds etc., the operator, the working environment.
- **Defined level of performance:** Performance is defined relative to the concept of **standard performance**
- **Standard Performance:** (standard rate of working) is defined as the rate of output which qualified workers will naturally achieve, without over exertion, averaged over the working shift, provided that they know and adhere to the specified method and provided that they are motivated to apply themselves to their work. The significance of 'standard time' is that it is the basis for all planning and costing of manufacturing operations, as it relates directly to the time taken by a qualified worker, working at standard performance to complete a given operation. Hence the number of operations completed in a shift = length of shift (minutes)/ Standard time for operation(minutes). Time standards are needed for: production planning; capacity; loading; scheduling; machine and operation balancing; costing and estimating; comparisons of alternative methods; incentive and payment schemes.

Steps in taking a time study

1. If the purpose of the time study is to establish a standard then it is **essential** that the operation has been subjected to method study first.
2. The worker to be studied must have the necessary physical and mental attributes, the necessary levels of knowledge and skill and be familiar with the operation ie well up the "learning curve".
3. Obtain and record basic information about the part/operation, the details of the process eg equipment used, jigs, tools, speeds & feeds etc., the operator, the working environment.
4. Observe the operation and break it down into a number of elements.
5. Over a number of cycles measure the time taken for each element and for each assess the effective speed of working of the operative (rating).
6. Convert the observed times to "basic times"

Note that basic time is not the standard time for the task. In order to establish the work content and then the standard time for the operation it is necessary to add fixed allowances to cover personal needs and basic fatigue, and variable allowance to cover Physical Strains (Force exerted, Posture, Vibration, Short cycle, Restrictive clothing), Mental Strains (Concentration/

anxiety, Monotony, Eye strain, Noise) and Nature of Working Conditions (Temperature and humidity, Ventilation, Fumes, Dust, Dirt, Wet).

It may be necessary to add allowances for unavoidable delays such as material handling or machine interference in multi - machine working. These are not part of the operation work content but are built into the standard time.

Standard Time is built up from the observed time and observed rating as follows:

- **Basic Time** = Observed time x Rating/Standard Rating
- **Work Content** = *Basic time* + Relaxation Allowances + Allowance for Extra work
- **Standard Time** = *Work Content* + Allowances for delay, unoccupied time, interference
- Or **standard time** = (observed time x rating) +(relaxation allowances + extra work allowances) + (allowances for delay, unoccupied time, interference)
- Or, Standard time = (observed time x rating) + allowances

b) (i)

95 % confidence limits are (Mean +/- ts/√n)

Note that it is important to use the t distribution in this case, and not the normal distribution, due to the fact that the sample size is very small and the population standard deviation is estimated from the sample.

Thus, t value is 2.776, n is 5.

	After 197 assemblies	After 397 assemblies
mean	120.2	105
sd (sample)	7.26	1.36
95% top	129.2	106.7
95% bottom	111.2	103.3

b) (ii)

The times from the second of the two sets of time study show a decreased time and much less variability. This is typical of a learning situation. The mean from the second study, 105s, is equivalent to 3514 TMU which is very close to the MTM time indicating that the operation has been well learnt.

b) (iii)

In order to calculate the total time we have to take account of the learning curve.

Learning curve eqn: y=Kx-A

(where y is time taken after x cycles and Kand A are constants)

Step 1: Estimate learning curve parameters, from the averages time after 200 and 400 cycles, either by calculating % learning, or by directly solving simultaneous equations.

% learning = 100*(105/120.2) = 87.3%

This gives values of A=0.195 and K =337.8

Step 2: Decide whether learning carries on after 400 assemblies.

The fact that the variation is significantly reduced suggests we may be near the limit of the learning curve for this operation performed in this way. This is confirmed by the fact that the average time is now very close to the time found from MTM analysis. In fact the time equivalent to 3500TMU is reached after 409 cycles (extra marks if any student calculates this). Hence we would be justified in assuming learning is complete and the remaining 600 operations are performed at a basic time of 105s.

Step 3: Find the total time taken for the first 400 operations by integating $y=Kx^{-A}$ between 0.5 and 400.5.

Total time = K(400.51-A -0.51-A)/1-A = 51989s

(Note limits, using 1 and 400 gives 51757s; using 1 and 401 gives 51862s.

Step 4: Find time for remaining 600 assemblies and add to time in step 3 to find total time

Time taken for remaining 600 = 600*105=63000s

Hence total time = 114862s = 31.9 hours.

BUT THIS IS THE BASIC TIME, WE NEED TO ADD ALLOWANCES FOR STANDARD TIME.

An estimate of allowances can be got from the actual time taken for assemblies 200 to 400 (7 hours given in question) and the basic time for assemblies 200 to 400 found from integrating the learning curve between 200.5 and 400.5.

Time = K(400.51-A -200.51-A)/1-A = 22304s

Ratio 7*3600/22304 = 1.13, equivalent to a 13% relaxation allowance, which is pretty typical of light assembly. Hence the total time for the assembly is 31.9*1.13 = 36.1 hours.

Assumptions: no forgetting at shift end or weekends; operator works at Standard performance.

This question was well answered and popular. Most students achieved almost full marks on parts (a) and (b).

--------------End of crib for question 5 --------------

SECTION C: **Question 6**

a) The question asks about how to plan in detail the layout of a new factory. This implies that there are 3 stages to consider:

- **Factory Layout**: The organisation of departments in the factory.
- **Department Layout**: The organisation of workstations (eg machine tools) within a department.
- **Workplace Layout**: The organisation at the workplace.

Prior to doing any form of layout planning it is necessary to gather base data. This is done by using the techniques of Method Study. Process and travel charts should be used to determine and record the process requirements and then the questioning routine should be used to critically examine these. Where we require time related data, for example, to determine how many of a particular machine tool are required, we use the techniques of Work Measurement.

Factory Layout

The organisation of departments in the factory is usually achieved by some form of Systematic Layout Planning, e.g.Muther,1973. Key Factors are

P - Product

Q - Quantitiy

R - Routing

S - Supporting Services

T - Time

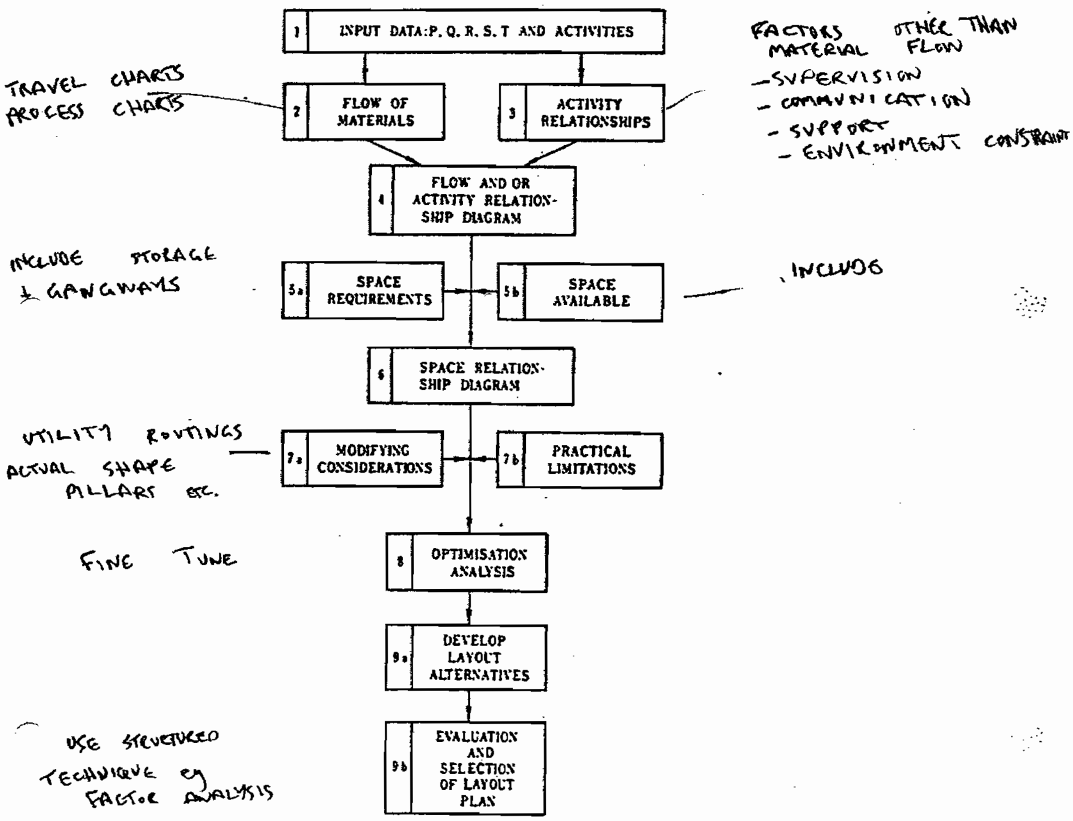
The main steps in the process are shown in the diagram overleaf (from Hitomi,'Manufacturing Systems Engineering')

New layouts are developed in an iterative and intuitive way making use of scale drawings, 3D models and computer assisted packages (eg Computerised Relative Allocation of Facilities Technique, CRAFT; Computerised Relationship Layout Planning, CORELAP) The computerised systems offer assistance by arranging space to minimise movement cost (generally a function of movement distance) against certain criteria and within certain restraints. NB They don't look to future flexibility or compromise.

Manual methods use activity relationship diagrams, space relationship diagrams, and trial and error on factory layouts.

Department Layout

The organisation of workstations (eg machine tools) within a department. Here we come up against the different types of process layout: functional, like machine types grouped together; or process machines aranged in sequence in a line or in a cell (as in GT). I would expect the students to outline the major choices, and the better students to outline some of the factors which might affect the choice of layout.



I would expect the students to mention some of the other factors which need to be considered when looking at departmental layout. There is the danger when looking at this subject that it can turn into the "science of lists", eg.the following items need to be considered:

- machines
- support structures, foundations
- handling: conveyors, cranes
- offices, gangways, catwalks, guarding, maintenance access
- storage and WIP buffers
- Services (heat ,light, power, air, steam, etc.....................and so on.

Workplace Layout: The organisation at the workplace.

The main factor affecting this stage is the Ergonomic design of the workplace. Here the tools of method study at the detailed levels can be used. The better students may give guidelines such as the following "Principles of motion economy"

Arrangement of the workplace

1. Definite and fixed stations should be provided for all tools and materials to permit habit formation.
2. Tools and materials should be pre-positioned to reduce searching. Tools should be easy to pick up and replace; as far as possible they should have an automatic return, or the location of the next piece of material to be

moved should allow the tool to be returned as the hand travels to pick it up.

3. Gravity feed, bins and containers should be used to deliver the materials as close to the point of use as possible. If similar work is being done by each hand, there should be a separate supply materials or parts for each hand
4. Tools, materials and controls should be located within the maximum working area and as near to the worker as possible.
5. Materials and tools should be arranged to permit the best sequence of motion
6. "Drop deliveries" or ejectors should be used wherever possible, so that the operative does not have to use his hands to dispose of the finished work.
7. Provision should be made for adequate lighting, and a chair of the type and height to permit good posture should be provided. The height of the workplace and seat should be arranged to allow alternate standing and sitting.
8. The colour of the workplace should contrast with that of the work and thus reduce eye fatigue.

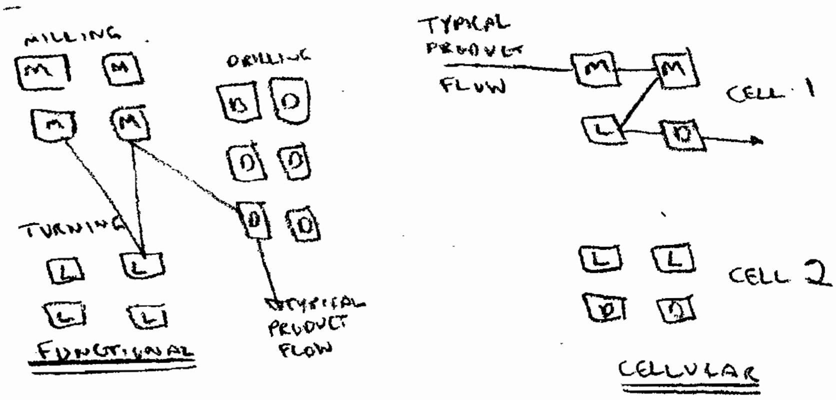
Students may introduce some principles of material handling at some point in the answer. Such as:

- Handling costs money and adds no product value.
- The best handling is none at all.
- Combine and Eliminate moves and handling operations wherever possible.
- Consider moving workers rather than materials.
- Mechanical Handling rather the manual handling wherever practicable.
- Straighten and Shorten moves.
- Use overhead space where feasible.
- Where possible, Pre-position for next operation before depositing material.
- Materials should move to next point of use, rather than an intermediate store; avoid double handling.
- Remember, 'material flow' is 'cash flow', stored materials represent 'dead' cash

These are obviously related to the main theme of the question but need to be covered very briefly as they are not directly answering the question.

b) A functional layout groups machines and processes together by type. For example, all the lathes would be together in one department, all the milling machines would be together in another.

A cellular layout groups together all the processes to manufacture a particular product or group of products. See diag.



Advantages of Cellular layout

Shorter Throughput times - less queueing and transport between processes, smaller transfer batches. Reduced inventory - due to above, less safety stock required and less buffering. Simplified planning and control - at factory level, cells make complete, routes less complex. Reduction of set-up times - due to commonality of product, familiarity, specialised tooling, learning curve effects. Improved quality, Improved productivity can also be achieved for similar reasons (commonality of product, familiarity, specialised tooling, learning curve effects.)

Cellular layout when combined with group technology can lead to improved designs, design for manufacture

Problems/ Disadvantages

Skills - With a functional layout, operators become highly single skilled, with cellular there is need for some multi-skilling to balance workloads. Plant - generally plant utilisation will be lower, and there is greater disruption if items of plant break down, and there is only one item in the cell. Control – at the cell level can become more complex, local autonomy in loading and scheduling. Product change – may cause problems if major cell reconfiguration is required.

As a highly descriptive question, many students were able to reproduce content from lecture notes. Better students added some critical analysis or insight with respect to the question being asked.

-------------End of crib for question 6 -------------

SECTION D: **Question 7**

a) (i)

A solid body has six degrees of freedom of mobility in 3D space: (Dx, Dy, Dz) and Rx, Ry, Rz.

The principle of Isotatism is the method of cancelling the degrees of freedom of a component, it has been defined as the "six point principle", i.e positioning a part by using six points of contacts on its faces. The 3-2-1 rule: Support points (1,2 and 3) eliminate (Rx and Ry) and (-Dz); points (4 and 5) eliminate (Rz) and (-Dx); and point (6) eliminates (-Dy).

a) (ii)

A good answer will first highlight the differences between Jigs and Fixtures.

- JIGS: Special design that holds, supports or is placed on a part to be machined. Locates and holds part BUT ALSO guides cutting tool.
- FIXTURES: Production tool that locates, holds and supports part. Fixture is fastened to table of a machine.

Jigs and fixtures ...

1. **Reduce non-productive time and increase production efficiency**: Work pieces can be set up in the fixture very quickly, while the fixture can be quickly set up in the machine tool by using special elements such as guide keys, setting blocks, guide sleeves etc.
2. **Help maintain machining accuracy**: As both the clamping position of the jig or fixture in the machine tool and the position of the workpiece in the jig or fixture are determined, and are kept constant for a batch of workpieces, the cutting tool can always keep a proper working position in relation to the workpiece during machining thereby ensuring stable machining accuracy
3. **Enlarge the application scope of machine tools**: Special purpose jigs and fixtures can replace the function of some machine tools, e.g. a non profiling milling machine can be modified from a normal, machine by attaching a special fixture allowing it to contour faces
4. **Release the working stress of the operator**: The technical skill level demanded of the operator can be lowered after applying special jigs or fixtures, the operation becomes more convenient and safer.

Design requirements:

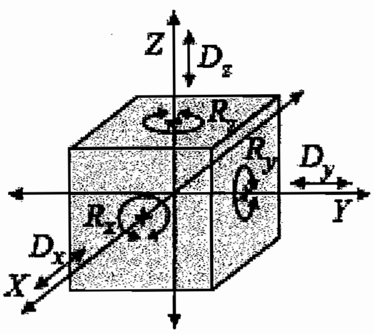
1. **Resist wear and material degradation**: Jigs or fixtures must be made of a suitable material in order to eliminate or minimise wear of the essential components, i.e pins, clamps, contact faces etc. The choice of material depends on the workpiece material and the number of operations the system is designed for.
2. **Location elements**: Location elements makes contact with the **datum surface** of the workpiece that secures the position of the workpiece in the jig or fixture. An example is a location post or location plate. These should constrain the workpiece as appropriate.

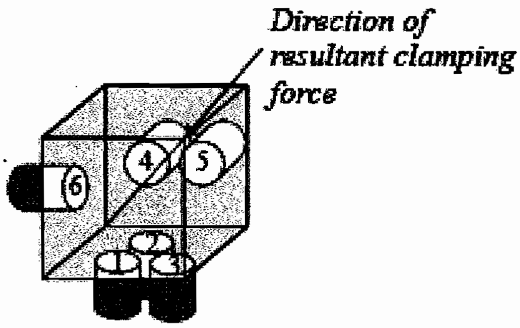
3. **Clamping devices**: Clamping devices are used to fix the workpiece to its correct position during machining; it can be powered or manual in its operation.
4. **Setting elements**: are used to set the relative position between the jig or fixture and the cutting tool or processing feature. An example of this is a drilling bush for drilling operations.
5. **Body of jig or fixture**: The body is the basic component that is used to connect the different parts of the jig or fixture while it attaches to the machine tool to provide a definite position in relation to the machine tool
6. **Other elements or devices**: Depending on the practical requirements of the processing operation, some jigs and fixtures may have dividing heads, positioning keys, locking nuts etc.
7. **Simplicity**: they should be simple.
8. **Quick loading and release**
9. **Poke-a-yoke**: fool proofing
10. **Not damage work pieces**. If the workpiece is fragile, then care should be taken in materials and forces.
11. **Greater precision**: than the part, where appropriate, up to 50% of the part tolerance.

b) The part needs to be constrained in all six directions, and also the fixture must provide suitable location in order to find the centre of the hole.

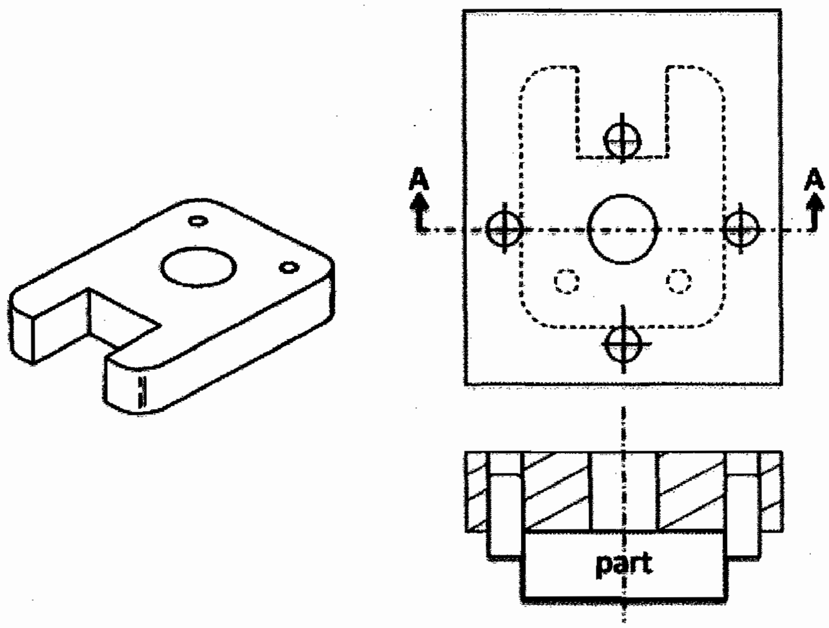
The location of pins 1,2 and 3 must be clear of the hole feature in order to drill the component, and there must be a clearance hole in the jig to enable drilling. Constraint in the z (upwards) direction might not be necessary, as the part is held against the tool by gravity.

Imobility is achieved when the workpiece is pushed against the support points and held in place by a clamping device.





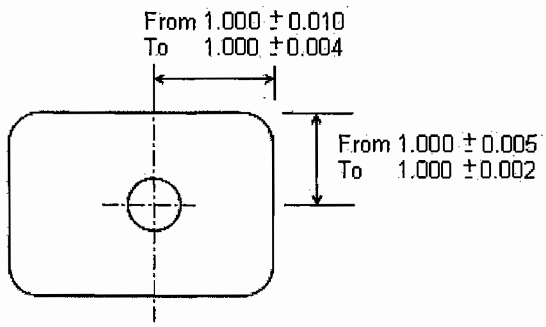
A potential embodiment of a jig design is shown below.



c) Jig and fixture tolerance must be such that the part features can be machined accurately. Part Tolerance

- Tooling tolerance to be 20% to 50% of part tolerance. ie. more precise.
    - Tolerances closer than 20% - Increase costs but not precision
    - Tolerances greater than 50% - do not guarantee desired precision
- Locators designed to fit part at any size within part limits

In this case the jig tolerances will be



Few students provided an adequate explanation for part (a). Part (b) was generally poorly answered, with students failing to apply the principles described in part (a). In particular, many students didn't adequately locate the part and failed to provide a clearance hole for the drill in the tool.

-------------End of crib for question 7 -------------

SECTION D: **Question 8**

a) Considerations:

Design Constraints: The complex geometry; requirement of constant thickness (to a high tolerance); the need for a high quality optical surface (Rz <25nm); and the need to coat the component with optical coatings (oxides on both sides) severely restrict manufacturing process options.

It is not possible to injection mould this part since this large component will suffer from melt flow lines that driven density variations which will affect the optical properties of the material.

It is not possible to machine this part as whilst the primary form could be created from a billet, the ability to obtain the surface finish (Rz <25nm) on one or both sides would be impossible on such a large and complex component.

An ideal process candidate would be Vacuum Forming, with the tooling cost being covered by the production volumes. Raw material will be in the form of Polycarbonate (PC) sheets of constant thickness and high optical quality without imperfections that would lead to refractive index variations and image distortion. The surface form must be established prior to the application of optical coatings, these are essentially complex oxides that will not distort and so must be applied at the end of the production cycle. The surface finish must be created BEFORE the surface form has been achieved.

The process steps would be as follows:

1. Obtain regular flat sheets of PC which are larger than the required component size. A series of operations must be conducted to obtain the required surface finish
    - Orbital grinding to near net thickness with a silica slurry to obtain ideal flatness
        - Non contact metrology step. Use large area interferometer to check the surface form, CMM probes are too limiting and are contact in nature.
        - Alternatively, use a laser triangulation sensor on a Cartesian gantry to check the surface form
    - Orbital polishing with a series of diamond pastes to obtain the required surface roughness
        - Non contact metrology step. Use large area interferometric microscopy to determine surface Rz levels
        - The above step is repeated should subsequent polishing steps are needed.
    - A temporary thin film protective coating should be applied at this point as it no longer to make contact with the surface (apart from on the edge with vacuum gippers). *Extra marks given here if this step is cited*
    - Since the sheet will be formed, it requires a vacuum forming tool and a large well controlled autoclave/oven and vacuum system

- Vacuum forming tools of this size must be machined from a billet, or formed sheets, and incorporate micro-porosity since the vacuum holes must not leave any witness marks on the sheet. The tool will probably be made from Al alloy and it's form must be qualified with a rigorous measurement programme (non contact large area laser scanning and triangulation are ideal techniques that could be employed, an alternative is speckle interferometery). This must be carried out at room temperature and at a temperature above the Tg of the PC since it may be close to the melting (softening) point of the PC and the tool may distort

- The complex shape will offer particular problems, since distorting a flat sheet to this form WILL produce a varying wall thickness in the part. Since the design requirement asks for a thickness of 25mm +- 100μm, it will be necessary to monitor the sheet thickness as it is formed very slowly to avoid unwanted distortions. An optical triangulation technique can be used to monitor sheet thickness as the part is formed in the oven (<250°C). In this respect, it may be necessary to provide a controllable vacuum system which is zoned across the tool in order to effect greater control over the sheet thickness, or the last resort is to use a two part forming tool, and deform slowly with the protective coating applied since it will not be possible to produce a tool of this scale with an Rz of <25nm.

- Once formed and checked for dimensions, the system must be profiled in order remove the land material. This must be done with the protective coating still place to avoid damaging the surface.

- The final stage is to apply the anti-reflection and reflection coatings. These coatings are very thin (n multiples of λ/2 where λ is the operating wavelength of the head up display system) or the likely wavelength of enemy lasers (typically in the range 500nm-1500nm.

- The canopy has its coating removed and is delivered to a coating chamber.

- The coatings are applied by PVD, using large area sputtering chambers. It is usually necessary to apply many thin coatings for enhanced performance (anything from 1-10 layers). The outer and inner surface will be coated separately sicne they will be made of different oxides.

- Once these steps are complete the final inspection will check for surface form; surface finish, and coating quality before the unit is despatched to Lockheed Martin.

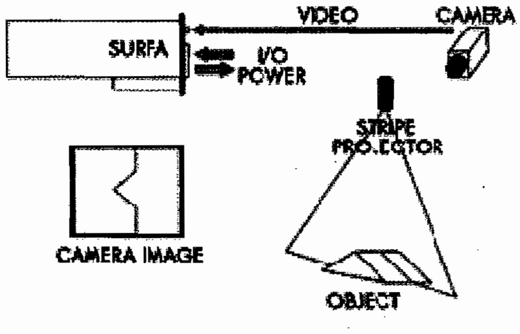
b) (i)

Surface Form:

- Large scale forms of this nature are best measured by a non contact technique called laser triangulation. Laser Stripe Triangulation

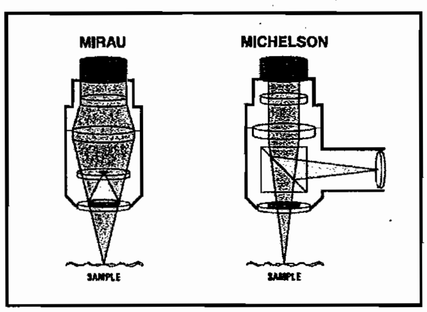
- A laser diode and stripe generator is used to project a laser line onto the object. The line is viewed at an angle by cameras so that height variations in the object can be seen as changes in the shape of the line.

The resulting captured image of the stripe is a profile that contains the shape of the object. The SURFA board uses DSP processing of video data to capture surface shape in real time at over 14,000 points per second, with a resolution ~ 10□m.



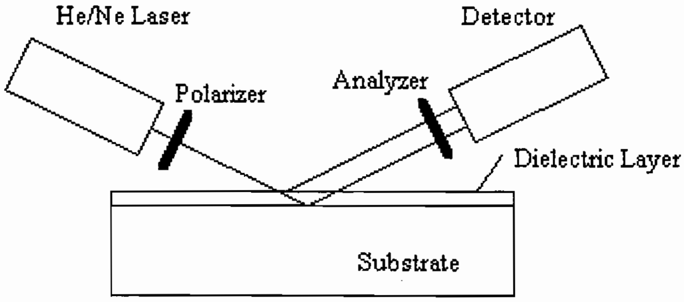
Surface Roughness.

- A white light or coherent interferometer can be used to determine surface roughness and form. The technique involves scanning the surface with light from one arm of a interferometric light source and counting the fringes as the surface is scanned underneath. The technique is very accurate ~nm, although surface effects can often give confusing data since we are relying on light reflection to obtain the data and this can be confused by scatter and shadowing..



Film Thickness (nm accuracy required)

- In process film thickness can be measured using an ellipsometer. The analysis is dependent on Snell's Law; when a beam of light strikes a material, some will reflect immediately, and some will pass through to the far side of the material before reflecting. By measuring the difference between the two reflections, the thickness of the device can be determined. The reflected light also undergoes a change in polarization; this change is used to calculate the refractive index and absorption coefficient.



b) (ii)

The life of the component will always be short given the hostile conditions in which it is being used (Sand, Snow, Ice, Dust etc). Pilots and technicians will always want to rub the surface (wiping it clean, de-misting) or give it knocks and bumps through general use. The best way of increasing the life of the component is to apply further coatings of scratch resistant transparent layers such as Indium-Tin oxide (ITO) to minimise the impact on the sensitive optical coatings. Or only let fully quailed laser physicists fly and fix fighter aircraft, then they will last a lot longer.

This was generally poorly answered, with students demonstrating relatively poor insight into the processes which might be appropriate for this component.

This question aimed to test the Manufacturing Engineering knowledge of the candidates. This problem was not detailed in lectures, although the various manufacturing processes that could be used were, including the measurement processes that would be employed for collecting data. Good students took note of the design constraints which not only restrict the process options but which force a particular sequence of process steps.

--------------End of crib for question 8 --------------