MASTER

Producibility of the LCD projection television LC2000

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LC2000

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Producibility of the LCD Projection television LC2000

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Summary

At Philips Novatronics the first Philips LCD projection television LC2000 is being produced. The production has just been started and is not running smoothly.
The production of the opto/mechanical part of the LC2000 proves to be a major problem. After analyzing the production of this part, which takes place in a clean room, 21 improvements which are economically feasible have been found.
A major production problem was that the adjustment range of the LCDs inside the projector with manipulators seemed too small. The analysis showed that the adjustment range met specification but that the manipulator got stuck against the brake and that the recohouse and the manipulators did not met specification.
As a spin off the analysis showed that the inspection criterium at the recohouse adjustment station can be enlarged from 4 to 7 pixels.
Furthermore the analysis showed that the adjustment action is not independent as was promised in the original theoretic model but completely dependent.

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1 Introduction

The Philips Television Laboratories have developed a new kind of television: LCD[1] projection television. This new kind of television projects the television picture on a screen like a slide projector. This picture is generated inside the projector by means of three LCDs.
Production facilities for the LCD projection television are at Philips Novatronics. Philips Novatronics is specialized in bestücken[2] of PCBs[3] and assembly of electronic products.
The production of the LCD projection television LC2000 has just been started and is not running smoothly. This has to be improved as soon as possible because orders have already been placed.

This study is an analysis of the product design of the LC2000 and the production process. It is aimed to point out the critical points for the production for example with respect to materials, mounting processes, tolerances and chosen production methodology.
It's second target is to give a judgement of the production process and give advise for the improvement of quality control and efficiency.

The LCD projection television LC2000 and its basic concept is introduced in chapter 2. Chapter 3 gives an general view of the production line of the LC2000. An essential point for shipment of a product is the packing. In chapter 4 a problem with the shock absorbing capability of this packing is investigated. The analysis of the production process is concentrated at the production in the clean room. For each station in the clean room a number of improvements is given.
Chapter 6 deals with an adjustment problem of the LCDs inside the projector.

[1]LCD: Liquide Crystal Display

[2]bestücken: placing and soldering of components on a PCB

[3]PCB: Printed Circuit Board

2 The design of the LCD projection television LC2000

The projection television LC2000 is shown in Figure 1. Almost the complete volume of the projector is occupied by the lighthouse. The optical components for generating the picture are situated inside this lighthouse. The rest of the space inside the projector is filled with electronic components.

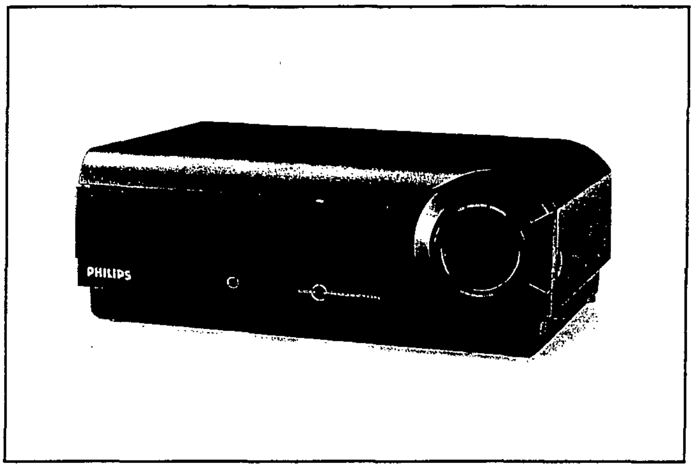


Figure 1: Projection television LC2000

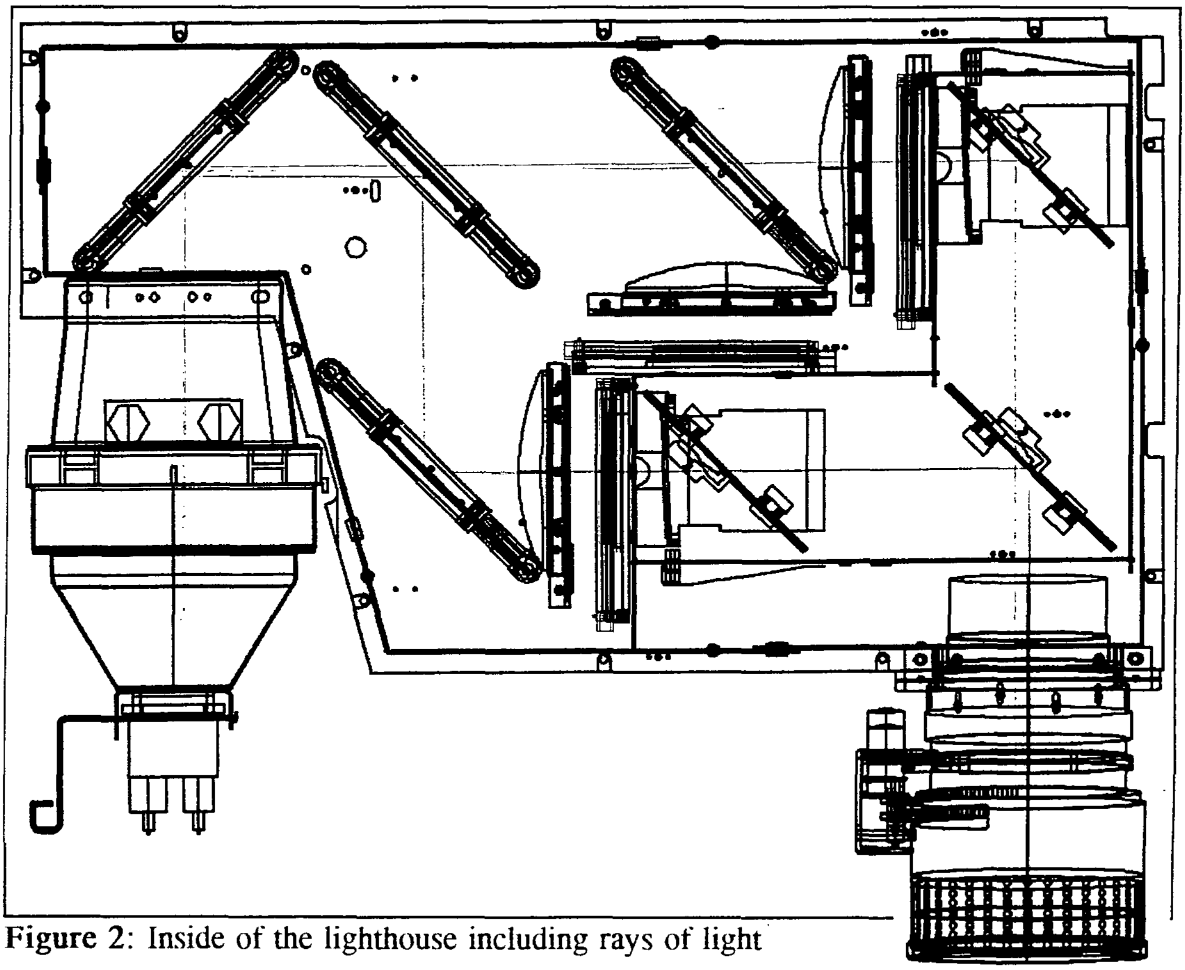


Figure 2: Inside of the lighthouse including rays of light

Figure 2 shows the inside of the lighthouse. The lighthouse consists of three parts: the lamphouse, the lighthouse and the recohouse (recombination house).

Inside the lamphouse are the lamp, a parabolic mirror and two integrator lenses. These components together create a rectangular beam of light which leaves the lamphouse towards the lighthouse.

The beam of light is split into the for television important three primary colours red, green and blue by means of dichroitic mirrors. Next the three beams are projected via a lens onto the LCDs. The LCDs are part of the recohouse and generate the television picture for each primary colour. In the recohouse the three beams are recombined to one single beam of light. After leaving the recohouse. The colour television picture leaves the projector by means of a projection lens system.

3 Production line of the LC2000

This chapter gives an overview of the production process of the LC2000 from incoming parts to projectors packed for shipment.

The production of the LC2000 takes place at Philips Novatronics. All parts are obtained from suppliers outside Novatronics.
When parts arrive at Novatronics they are inspected if necessary. This depends on the quality of previous supplies. After inspection the parts are put in stock. At the same time this new stock is fed into a stock-control-system. Now parts are ready to be used in production.

Figure 3 shows the production of the LC2000. It can be divided into three parts:

- Bestücken of PCBs
- Assembling of the lighthouse
- Joining the above mentioned parts onto a frame, together with the rest of the parts.

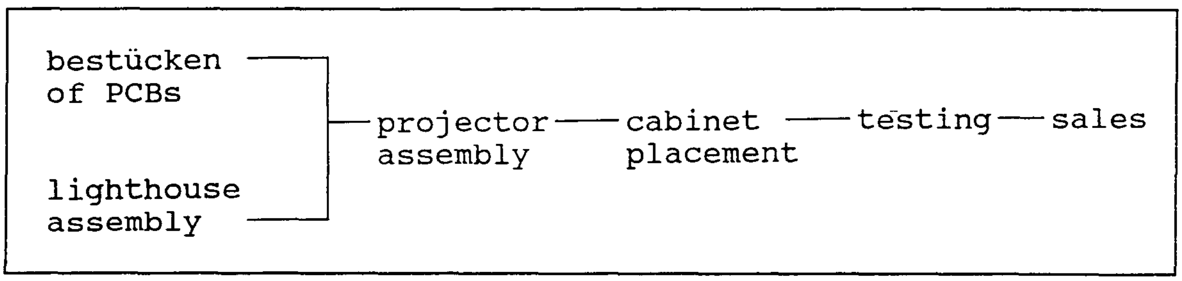


Figure 3: Diagram of the production of the LC2000

Bestücken of a PCB involves placing and soldering of electronic components on a Printed Circuit Board. This process can be divided into two parts. First all standard electronic components like resistors, transistors and capacitors are placed and soldered automatically.
The second part involves placing by hand and soldering of transformers, heatsinks, connectors and so on.
After the PCBs have been mounted they are transferred in batches to the

Projector Room for assembly in the LC2000.

The assembly of the lighthouse of the LC2000 takes place in the clean room. Parts from stock are cleaned if necessary before they are brought into the clean room. In the clean room the parts are put together by hand to form the lighthouse, which is the opto/mechanical hart of the LC2000.
Assembled lighthouses are kept in stock in the clean room until they are transferred to the Projector Room.

In the Projector Room all sub-assemblies come together. The pre-assembled PCBs are mounted to the bottom side of the frame. The lighthouse is assembled on the top side of this frame. Also the cooling fan, a handle bracket and the local keyboard are mounted to this side of the frame.
Next the projector is tested and electrically adjusted.
Then the bottom, front and top cover plates are mounted on the frame. Finally some small cover plates, stickers and the carrying handle are mounted and the LC2000 is ready to be packed.

Then LC2000 is transported to the packing area. Here it is packed in a cardboard box. Together with the buffers inside, this cardboard box meets the UPS transportation rules.
From here the boxes are moved to the shipping zone were they are stored until they are being shipped to the customer.

4 Cardboard box

The LC2000 projectors are packed in a cardboard box for shipment. This box has to apply to UPS transportation regulations. For the LC2000 this means that the projector inside its packing has to withstand ten free falls from 76 cm high onto a concrete floor. One on each of the sides of the box, three on the edge and one on a corner.
After shipment to the USA the following complaint came forward: Convergence shifts in height direction of the blue LCD.

It was believed that the construction of the recohouse caused this shift. Several vibration and drop test were executed on separate recohouses and recohouses inside a complete projector (see reports on drop tests P .v. Os). This confirmed the complained but no cause for the problem was found in the recohouse.
Then I noticed that the carrying handle is very close to top of the box and that the carrying handle is right above the blue LCD in transport position. When the carrying handle was introduced onto the projector only changes inside the box were made to make the projector including the carrying handle fit inside the box (see Figure 4). There is enough space available inside the box to make the carrying handle fit but this space is ment to be used as braking distance. So by placing the carrying handle in this space the braking distance is shortened which invokes higher g-forces on the projector in case the box is dropped.

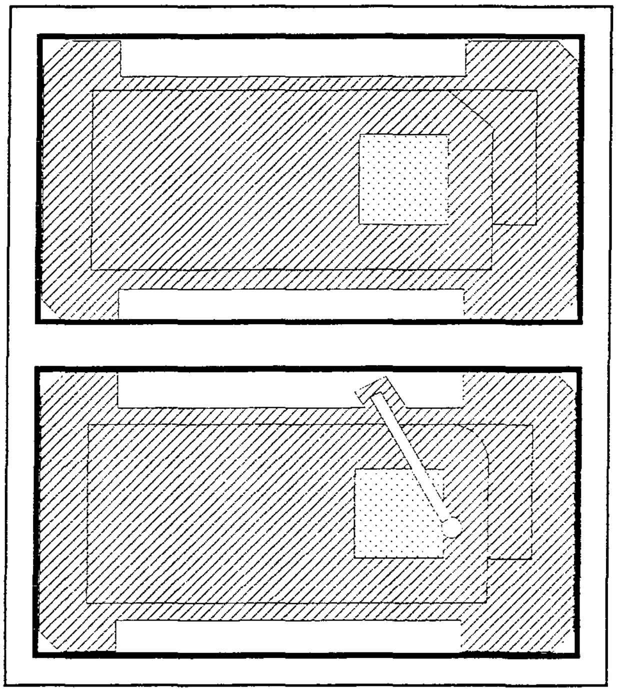


Figure 4: Projector without and with carrying handle in box

A new drop test was preformed to see if the handle would hit the top of the box which would prove that the braking distance left is to short.
The test showed that the carrying handle indeed touched the top of the box. After the height of the box was changed a new drop test was executed. This resulted in no convergence shift so the new box was introduced for transportation.

5 Analysis of the production in the clean room

The production in the clean room will be analyzed in this chapter. The analysis is performed as follows:

- Division of the production process in parts
- Analyze for each part: input
  actions
  output
- Search for solutions for problems
- Economic feasibility
- Present/implement improvements in design and/or production process.

Before the production in the clean room can be analyzed separately form the rest of the production line the interfaces between the clean room and the rest of the production have to be analyzed.

5.1 Interfaces of the clean room

The input of the clean room consists mainly of bought parts. There are two main problems with this input.
First of all there is a problem with the stock-control because it too often occurs that parts are not available in time.
Several causes can be brought up for this problem.

- programming failure: computer orders to late
- human error:
  - fail to keep program up to date by not entering used or rejected products
  - actual number of parts does not correspond with computer data

Two actions have been taken to correct this problem.

- The number of parts in the clean room have been recounted.
- Rejected parts are reported once a week to the stock-control-system.

Besides the fact that parts do not arrive in time they do not match specifications. In production the problem is first discovered when mounting or at an inspection or adjustment station.
The parts are sent to the production line because there is no incoming inspection after the parts are released for production.
Two actions have been taken to prevent wrong parts from being mounted. Firstly some parts are checked in production before mounting. Secondly manufacturers of some parts are informed about the problems with their parts and asked to correct this as soon as possible.
To be sure of 100% good parts in production, which is a must for efficient production, incoming inspection of all parts in needed until a 100% guarantee, for example inspection reports of the supplier, of good parts is available.
The incoming inspection will repay itself by less rework in production.

The output of the clean room consists of the lighthouse sub assembly. There is one main problem with the output.
When a lighthouse is returned to the clean room most complaints deal with bad picture quality.
One of the causes of bad picture quality is convergence failure[4]. This convergence failure can have the following causes:

- Wrongly mounted part(s)
- Wrongly adjusted convergence
- Transportation damage

To prevent parts from being mounted wrongly the design has to be changed in such a way that parts can only be mounted in one way. Most parts are designed this way but for example the mirrors are not. These mirrors can be mounted back to front which causes convergence shifts. To reduce this particular problem the markers on the mirror that indicate the front of the mirror should be made as big as possible. Now the marker is a tiny dot of a

[4]Convergence failure: see paragraph 6

pencil.

Transportation damage can be caused by too high g-forces. The g-force can be calculated as follows:

$$U_p = m * g * h \tag{1}$$

$$U_k = \frac{1}{2} * m * v^2 \tag{2}$$

(3) is valid for a free falling object.

$$U_{p_{falling}} = U_k \tag{3}$$

(4) is valid during impact of a object.

$$U_k = U_{p_{impact}} \tag{4}$$

Combination of (3) and (4) leads to:

$$U_{p_{falling}} = U_{p_{impact}} \tag{5}$$

$$m * g_{falling} * h_{falling} = m * g_{impact} * h_{impact}$$

$$g_{impact} = g_{falling} * \frac{h_{falling}}{h_{impact}}$$

with: $g_{falling}$ = 1 (gravitation) = 10 m/sec^2
$h_{falling}$ = height of which product is dropped
h_{impact} = braking distance

$$g_{impact} = \frac{h_{falling}}{h_{impact}} \tag{8}$$

The lighthouses are assembled on metal table-tops. Also the transport carts have metal table-tops. The braking distance of a metal lighthouse on a metal table top is virtual zero. As a result of this the g-force is nearly infinite (see (8)).

During this transport several bumps have to be taken. This can cause convergence shifts of the LCDs because of too high g-forces.

The lighthouses should be handled carefully until they are mounted inside the projector and the projector is standing onto its shock absorbing feet. Damping material on all surfaces on which the lighthouse is being put is necessary to prevent convergence shifts caused by too high g-forces.
Introduction of damping material is a low cost investment which enhances quality and reduces rework.

Besides that the personnel has to be well trained and motivated to execute their job well. Recently newly introduced personnel in the clean room have had an introduction about the apparatus they are assembling.
Training will repay itself by a more efficient production; less fall off, higher quality and faster assembly.

5.2 Division of the production process

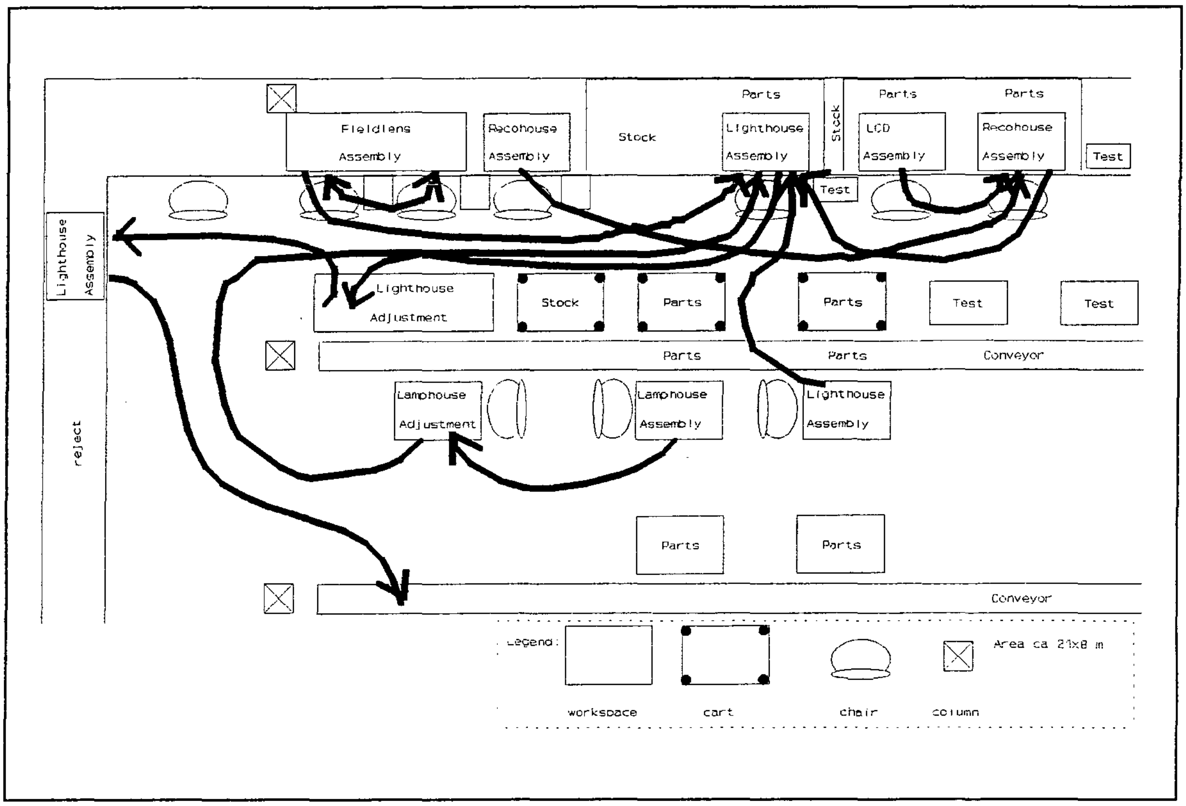


Figure 5: Part of the clean room where the lighthouse production is situated

Figure 5 gives an overview of the part of the clean room were the production of the LC2000 takes place. This is approximately one sixth of the complete clean room. The rest of the clean room is used for other production and storage room for already cleaned parts.

The analysis will deal with all stations shown in Figure 5 separately.

The routing between the stations is also drawn in Figure 5. This reveals that this routing is not optimal. This routing has recently been changed by rearranging the stations (see Appendix A).

The diagram of the production flow in Figure 6 has a kind of up side down bottle shape. The inevitable bottle-neck is not found at station 7 but at station 8. This will be shown in paragraphs 5.3.7 and 5.3.8.

5.3 Station by station analysis of the clean room

5.3.1 Station 1: LCD assembly

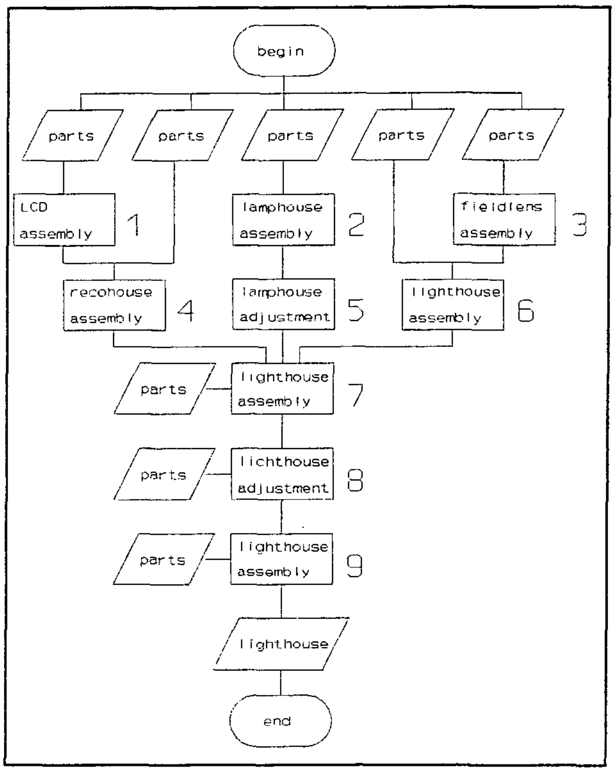


Figure 6: Production flow of the lighthouse

Besides an assembly station this station is used as an incoming inspection station for the LCDs. The following problems are present in the assembly part. The analyzer is fixed to the LCD by means of a saw cut head screw. This causes the screwing process to take more time than necessary. Also the risk of damaging the analyzer with the screwdriver is increased. The screwdriver itself enlarges this danger because its handle is very slim. As a result of this it is difficult to enforce enough torc on the screw.
The fixing can be improved by using torx screws and a screwdriver with a thicker handle.
The problem with improvement of the screw is that the dimension of the screw, M 1.7, is not a standardized one. This makes it hard to find suppliers for this screw. A better screw driver can be implemented right away.
This low cost change will fasten mounting so it will repay itself.
To protect the LCD from being electrically damaged by ESD[5] during production a clip is attached on the electric foil which is connected to the LCD. This clip is difficult to place.
This clip has previously been used for the production of the CDM3 and nobody knows any specifications of this clip. Obvious this clip is not suitable for foils of 30 μm like the one used here. (see Appendix B)
The problem can be solved by using a clip with lower clamping force or a

[5]ESD: Electro static discharge

paperclip.
Introduction of another clip is paying because less foils are damaged during mounting of the clip. Sometimes the clip is not attached which can cause damage to the LCD. Furthermore an easy to mount clip works faster.

The incoming inspection action of the LCDs proves to be very difficult. This action is aimed at removing dust from the LCDs. The problem is that this dust is difficult to distinguish from other obscurations like scratches and pixel failures. This causes that hard to remove dust is considered as an obscuration of the LCD itself. This wrongly cleaned LCD is sent to the next station. This next station is not in the clean room but in the life test room. This room is not clean at all. Here LCDs are tested for pixel failures and other obscurations like scratches. But here new dust falls on the LCDs which frustrates this test.
This problem can be solved by combining these two stations in the clean room. This has the following advantages:
- Only one operator is necessary
- The complete test is quicker because :
    - No transportation between stations
    - No rejected parts between stations

There is one disadvantage:
- A dark room has to be build inside the clean room

This dark room can be combined with the new station for the lighthouse adjustment that is planned (see paragraph 6.3.6).
Each LCD that is rejected costs about $300,- and by transporting the LCDs from one station to another (outside the clean room) there is a risk of damaging a LCD.
From this it can be concluded that these two stations have to be combined as soon as possible. Although a new station is expensive to built the pay off is enormous. When one LCD more is saved in this new station it $300,- is saved. Besides the combination of two stations into one saves one operator.

5.3.2 Station 2: Lamphouse assembly

A copper and plastic band has to be put between the insulating ring and holder 1. This action is difficult and time consuming. It can be improved by making a chamfer on the insulating ring (see Figure 7). Problem here is that the modification of the insulating ring is most certainly too expensive for the small number of products jet to be produced.

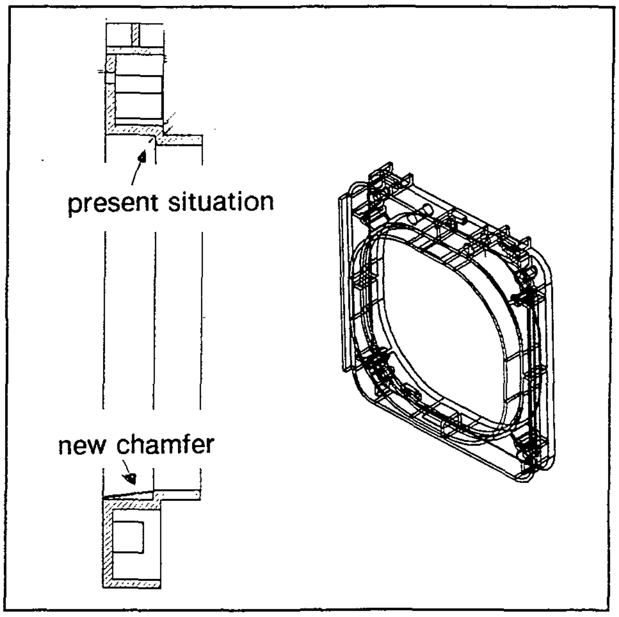


Figure 7: Chamfer on insulating ring makes mounting easier and faster

The insertion of the pins in the lighthouse is also a difficult action.This is caused by the fact that the pins are not self centering. This can be improved by making the chamfer on the top pin bigger (see Figure 8 and Appendix C). This small change will repay itself by faster mounting.

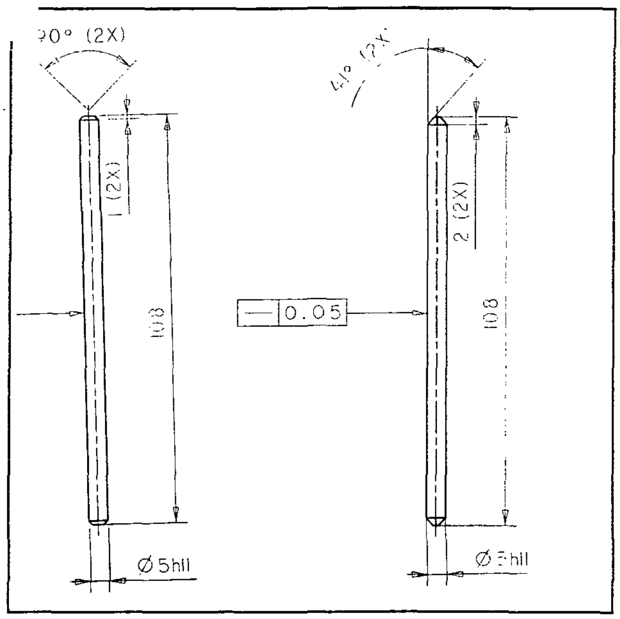


Figure 8: Old and new pin with chamfer for easy mounting (redesigned on Suntools CAD-system)

5.3.3 Station 3: Fieldlens assembly

The flow rate of the vacuum system for hardening the glue is too low for effectively hardening the glue. This is caused by the fact that the vacuum system is built the wrong way. By splitting up the vacuum hose three

times the resistance in the system causes the pressure at the intake to drop to virtually zero.
This can be avoided by using a hose with a bigger inside diameter. With a good functioning aerating system the hardening time of the glue of the fieldlenses can be brought back from 24 hours to the original 4 hours.

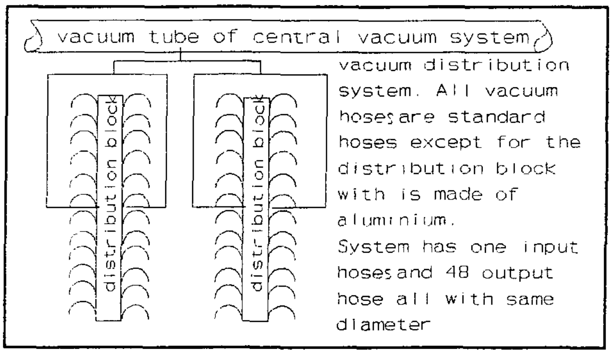


Figure 9: Vacuum system

This cheap change of the vacuum system makes it possible to produce more than 16 apparatus a day, because this is the maximum amount of fieldlenses that can be hardened with this system. Besides production is less dependent of the hardening time which makes production more flexible.

5.3.4 Station 4: Recohouse assembly

There are two problems with the mounting of the tap lock in the recohouse. Firstly the tap lock is a very small component which easily slips through your fingers. Secondly the tap lock has to be glued to the recohouse. This glue has to dry before further assembly on the recohouse can be done. As a result of this a small stock of drying recohouses is present in production.

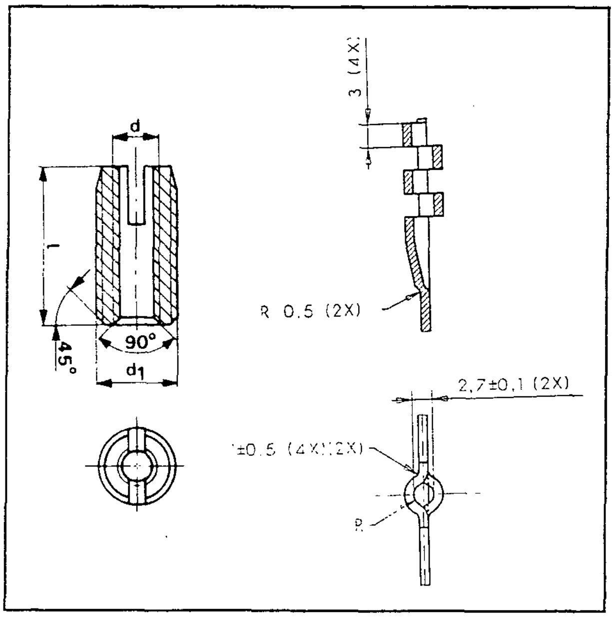


Figure 10: Tap lock and new system

Both problems disappear when the tap lock is replaced with the same system as is used in the lighthouse (see Figure 10). This makes this change economically feasible.

The mirror clamp at the top of the mirrors is integrated in the recohouse (see Figure 11) This clamp is for one time use only. When a mirror has to be replaced the complete recohouse has to be replaced.

This can be avoided by using the same system as at the bottom side of the recohouse. Here the mirrors are clamped to the recohouse by a separate clamp. The present used clamp is difficult to place. This is caused by the fact that the clamp has to stick behind a bar. When doing this the clamp often slips from your hand. This problem can be solved by redesigning the clamp as shown in Figure 12 and Appendix D. This design has already been tested and proves to work well.

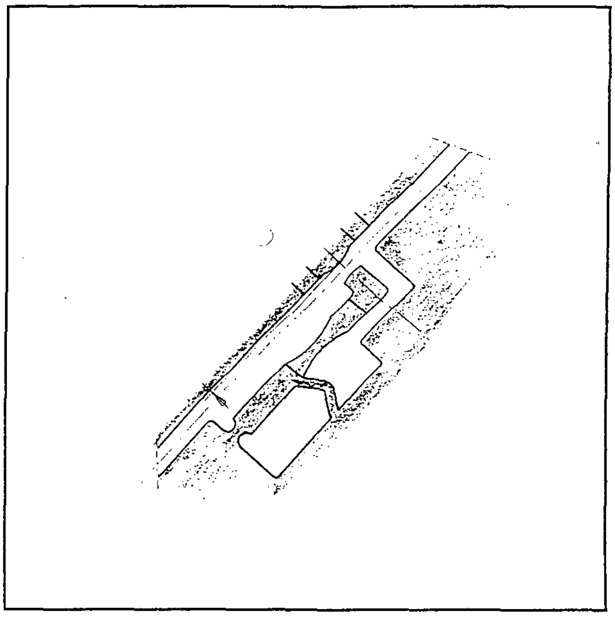


Figure 11: Integrated mirror clamp of the recohouse

This change of the mirror clamp is not expensive and repays itself by improved mounting.

The unadjusted recohouses that leave this station have to be within adjustment range. Theoretically this adjustment range has to be about 1 mm. In production only recohouse which have to be adjusted maximum 0.5 mm prove to be adjustable. An analysis of this problem is presented in chapter 6.

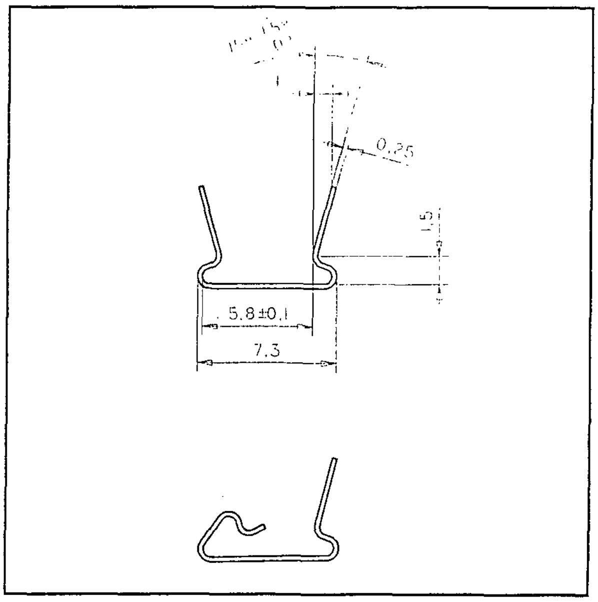


Figure 12: Redesigned mirror clamp on Suntools CAD-system

5.3.5 Station 5: Lamphouse adjustment

At this station the output of an assembled lamphouse is adjusted. The adjustment criteria at this station are subjective. As a result of this a lamphouse can never be adjusted to best position. Secondly the adjustment result depends on the operator. Thirdly a subjective adjustment criterium leaves room for discussion about the quality of the adjustment.
It is better to make these criteria objective by installing cameras into the adjustment set up. These cameras can register the desired light output and translate this into an objective reading on a scale.
The price of quality is hard to measure. But subjective criteria are always costing money as a result of longer adjustment time and possible rework.

5.3.6 Station 6: Lighthouse pre-assembly

To prevent dust from entering the lighthouse a foam strip has to be sticked upon the sides of the lighthouse. There are three problems with this foam strip.
The foam strip has to be sticked on the top side of the sides of the lighthouse. These are metal plates of 1,2 mm thick so it is difficult to stick the foam strip onto this thin side.
The second problem is caused by particles that come off the foam strip during mounting. This causes loose particles within the clean room and within the lighthouse.
When parts come off the foam strip dust can enter the lighthouse through the caused holes.
These problems can be solved by sticking the foam strip on the bottom plate instead of on the sides.
This change has been introduced without any costs.

5.3.7 Station 7: Lighthouse assembly

The main problem at this station is mounting the top cover plate at the lighthouse. This is caused by the eight mirror pins inside the lighthouse. These pins have to fit through holes in the top cover plate. A chamfer on top of the mirror pins has been made to make mounting easier. This did not work because the position of the mirror pins is not defined until the top plate has been mounted.

By replacing the pins by mirror clamps (see Figure 13 and Appendix E) that are click fitted in the bottom and top plate the mounting is improved. Besides an improved mounting this solution has two other advantages.

First only four parts instead of ten parts are needed to mount one mirror.This results in less different parts and faster mounting.

Secondly it is easier to open the lighthouse in case of service. Instead of removing eight screws no screws have to be removed.

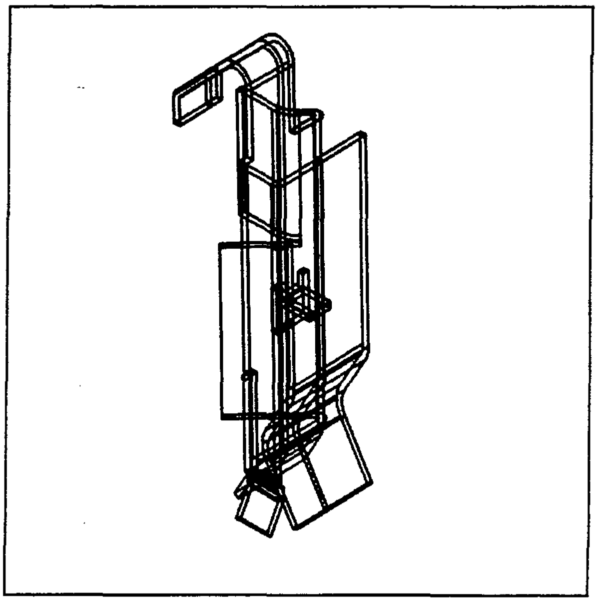


Figure 13: Mirror clamp for improved mounting of the mirrors in the lighthouse. (designed on Suntools CAD-system)

These facts make it economically feasible to change the mirror clamps.

Mounting of the foamring around the projection lens is difficult because the ring does not fit tight around the lens. The problem can be solved by using a smaller ring. A material saving so a cheaper and better solution is to stick a foam strip on the lens.

The same foam strips as described in paragraph 5.3.7 have to be sticked upon the sides of the lighthouse with the same problems and solution.

5.3.8 Station 8: Adjustment of the lighthouse

The adjustment criterium for the focus adjustment is subjective. This gives the same problems as stated in paragraph 5.3.5. Also here the adjustment can be made objective by installing cameras for focus adjustment. This has been tested at the TV lab and proved to work well.
The adjustment of the lighthouse is a difficult task (see chapter 6) which only can be preformed efficiently by a trained operator. As a result of this the adjustment is dependent on the operator which invokes a risk for production. At least three well trained operators should be available for adjustment to eliminate this risk.
This investment in operators will pay off, because if the now one available operator is ill or on holidays, production levels will not be met.

5.3.9 Station 9: Final assembly of the lighthouse

The mounting of the rubber dustcaps is difficult. The caps fit tightly in holes in the lighthouse. By making the rubber of which the dustcaps is made of more flexible the mounting will be made easier. This can be done by using another material or making the dustcap thinner. This low cost change will repay itself by reduced mounting time and cheaper dustcaps in case of the second solution.

5.3.10 Ergonomics

Ergonomics at most stations can be improved, especially the inspection and adjustment stations.
At the LCD inspection station there are two problems with the light. Firstly there is not enough light for optimal inspection of the LCDs when they are cleaned. Secondly there is too much light when the LCD is inspected on a screen. This screen is not suitable for this inspection of the LCDs for the following reasons:

- The screen is very rough which makes inspection difficult.
- There are obscurations on the screen itself.

These points can be improved when the station is being moved and integrated with the lighthouse inspection station.

At the adjustment station there are also problems with the screen. Focus adjustment on this screen is very difficult for the following reasons:

- The screen is rough.
- The screen moves out of the focal plane when it is being touched.

The focus and convergence adjustment is difficult because a close look at the screen is obstructed by the lighthouse being adjusted.

As a result is very difficult to make the best possible adjustment. These problems can be solved by installing the cameras as mentioned in paragraph 5.3.8.

At the assembly stations there are problems with the screwdrivers. First of all the screw bits are bend and do not fit tightly in the drivers. This makes them wiggle which results in reduced screw capability. A second problem is the fact that there is no proper place to store them when they are not used. Because of this there is danger of dropping them accidently on the floor and damaging the screw drivers.

The second problem has been solved by mounting hooks on the tables to hang the screwdrivers on.

6 Adjustment range of the LCD

All assembled recohouses are checked before they leave the recohouse assembly station. This check is aimed at checking if the LCDs are mounted within the adjustment range of the manipulators.
Its seems that the adjustment range is too small to correct all errors that are caused by the tolerances.
An analysis has been executed to find a solution for this problem. First data of the present adjustment were collected. Secondly an accurate model of the convergence and focus adjustment range has been developed. Thirdly the collected data and the calculations are compared. From this solutions for the problem can be drawn.

6.1 Data collection

For data collection first has to be decided where to collect data, what data to collect and how to collect this data.
Data has to be collected at two points. Once before and once after adjustment. Collecting data before adjustment is possible at the check point at the recohouse assembly station.
Collecting data after adjustment has to be done after the lighthouse is completely finished and before it is transported to the projector room. So the only place to collect this data is at the stock of adjusted lighthouses in the clean room.

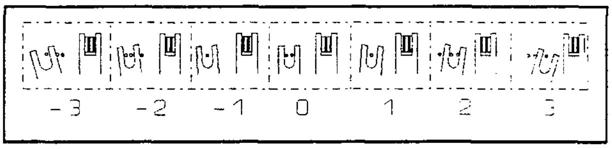


Figure 14: Position of the lever of the manipulator with corresponding scale

At the checking station it is possible to see what the convergence shifts of the red and blue LCD are with respect to the green LCD. This is done by counting the amount of pixels of the convergence shift. This pixel shift is translated into the shift in mm. For this data collection a data collection sheet has been designed (see Appendix F).
Collecting data at the stock in the clean room can only be done by removing

the dustcaps from the lighthouses. Then the position of the levers of the manipulators is visible. To note down these positions the scale presented in Figure 14 had to be designed. The positions can be translated into shifts in mm with the computer program of the manipulator presented in paragraph 6.3.

After a first analysis it appeared that positions +3 and -3 (see Figure 14) almost never occurred. This can be explained by the pre adjustment at the recohouse assembly station. When the check at the recohouse assembly station shows that it is probably impossible to adjust the LCDs properly the LCDs are remounted to try to position the LCDs well within the adjustment range.

For the convergence lever of the manipulator position -3 never occurred. After analyzing it proved that the manipulator lever got stuck against the brake that prevents this lever from moving unwanted (see Figure 15). The manipulator was changed to make full advantage of the designed adjustment range by removing a small part form the manipulator (see Figure 16)

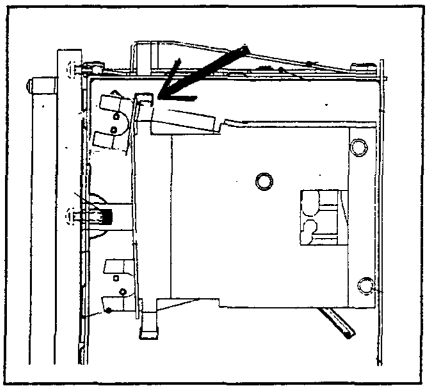


Figure 15: Convergence lever of manipulator stuck against brake

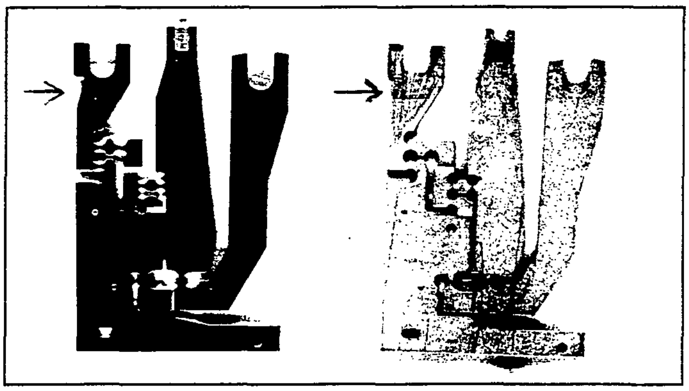


Figure 16: Alteration of the manipulator in order to prevent collision with brake

6.2 Original theoretic model

Figure 17 shows a plane, which represents the LCD that has to be manipulated. To define this plane in space three points are necessary. These points are located in such a way that the so called thermal centre TC is located in the centre of the plane. By moving these three points in two directions (u,w) the plane can be moved in all six degrees of freedom (x,y,z,φ,ψ,ϑ).

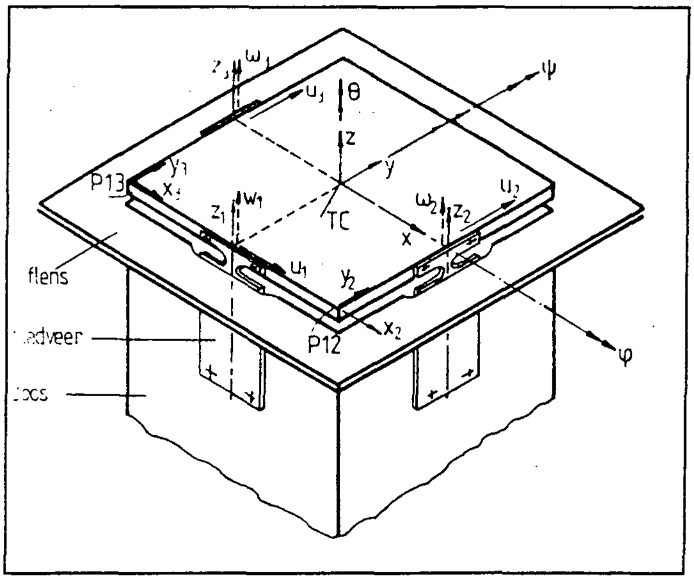


Figure 17: Model of LCD adjustment system

When the adjustment procedure is formulated in the coordinates x,y,z,φ,ψ,ϑ for the point TC, there is no effectively converging nor independent adjustment procedure possible. The following matrix is valid here:

$$\begin{bmatrix} x \\ y \\ z \\ \varphi \\ \psi \\ \vartheta \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/2 & 1/2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/2 & 1/2 \\ 0 & 0 & 0 & -1/b & 0 & 0 \\ 0 & 0 & 0 & 0 & -1/2a & -1/2a \\ 0 & 1/2a & -1/2a & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u1 \\ u2 \\ u3 \\ w1 \\ w2 \\ w3 \end{bmatrix}$$

a = distance manipulator 1 to TC

b = distance manipulator 2 or 3 to TC

In this case y and ϑ are both only (linear) dependent of u2 and u3. Z and ψ are both only (linear) dependent of w2 and w3. As a result of this, convergence of this adjustment procedure is not big.

It is better to formulate the adjustment procedure in the coordinates x2 or x3, y2, y3, z1, z2, z3. Focusing the LCD means positioning the points z1,z2,z3 by means of respectively w1,w2,w3. Converging the point P12 or the point P13 in x-direction means manipulating x2 or x3 with u1. To position P12 in y2-direction means moving u2 (P13 is the rotation centre (pool) for this movement). To position P13 in y3-direction means moving u3 (P12 is the rotation centre (pool) for this movement). This procedure is independent. The matrix notation for this procedure looks like this: (Koster, 1990).

$$\begin{bmatrix} z1 \\ z2 \\ z3 \\ x2(=x3) \\ y2 \\ y3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} w1 \\ w2 \\ w3 \\ u1 \\ u2 \\ u3 \end{bmatrix}$$

6.3 Model of the manipulator

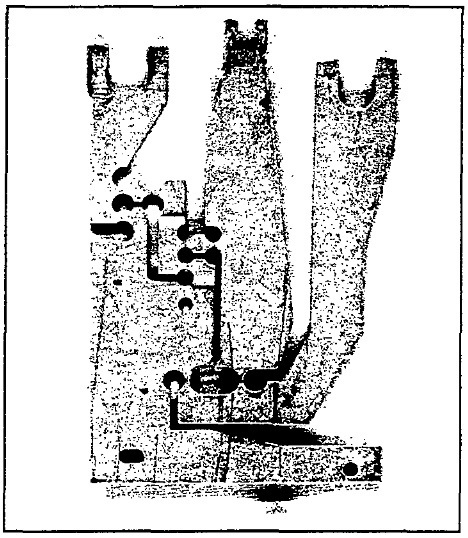


Figure 18: Manipulator

To move the three points which define the plane of the LCD a 2-d-manipulator shown in Figure 18 is designed. The position of the top of the centre lever is the output of the manipulator and controls the u-direction and w-direction of the three points. The input for this movement is given by means of the two other levers.
The short convergence lever is used for positioning the top of the centre lever in u-direction. The long focus lever is designed for manipulating the head in w-direction.

The manipulator can be represented by means of three four-bar-mechanisms shown in Figure 19. When the convergence lever is not moved the manipulator can be modeled as one four-bar-mechanism (Figure 20). When the focus lever is not moved the manipulator can be modeled by two four-bar-mechanisms (Figure 21).
To calculate the movement of the top of the centre lever of the manipulator first of all a mathematical model of a four-bar-mechanism has to be designed.

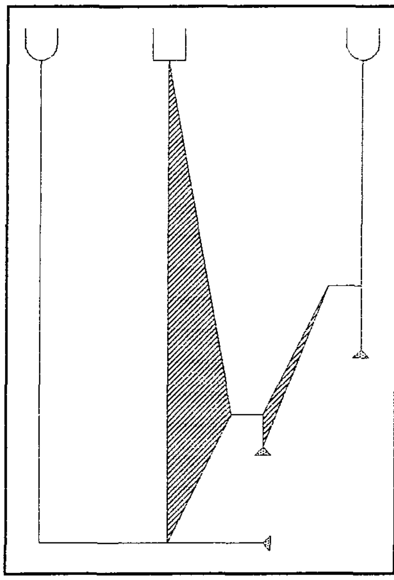


Figure 19: Model of manipulator

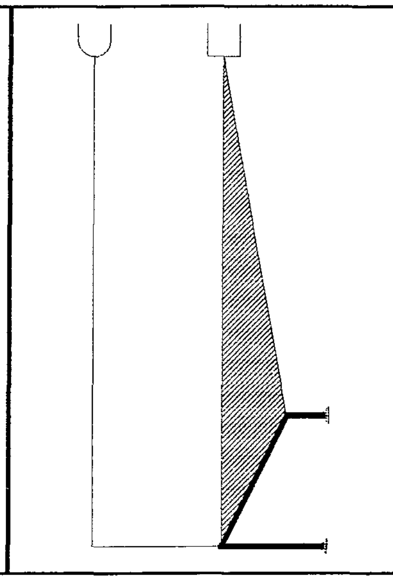


Figure 20: Model of focus part of manipulator

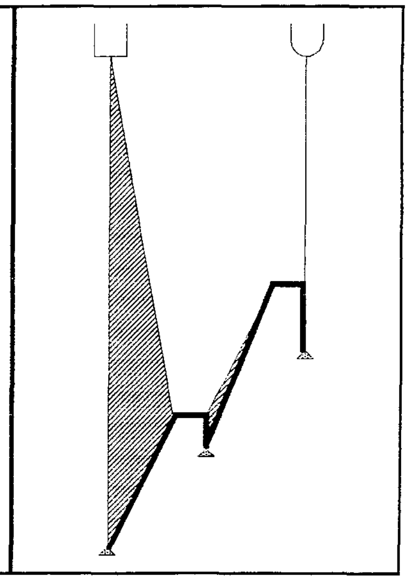


Figure 21: Model of convergence part of manipulator

The rotation of bar 1 in Figure 22 is the input of the four-bar-mechanism. The output is the position of point number 2. This position can be mathematically represented by formula (9):

$$(x_2+\Delta x_2)^2+(y2+\Delta y_2)^2=r_2^2 \qquad (9)$$

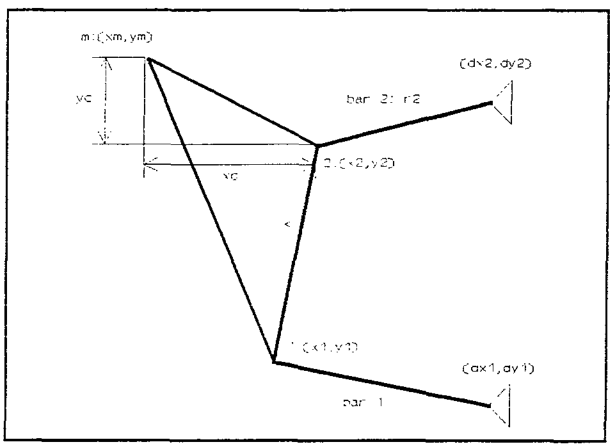


Figure 22: Four-bar-mechanism with coupling plane

The bar between point 1 and point 2 can be represented by formula (10):

$$(x_2-x_1)^2+(y_2-y_1)^2=k^2 \qquad (10)$$

The coordinates x1 and y1 of point 1 in formula (10) are dictated by the input, so they are known. Two new formulas - (11) and (15)- can be derived from formulas (9) and (10) to calculate the output x2 and y2 (see Appendix G).

$$x_2=\frac{y_2C_1+C_2}{C_3} \tag{11}$$

wherein:

$$C1=2(y_1+dy_2) \tag{12}$$

$$C_2=k^2-r_2^2-x_1^2+dy_2^2+dx_2^2 \tag{13}$$

$$C_3=-2(x_1+dx_2) \tag{14}$$

and

$$Ay_2^2+By_2+C=0 \tag{15}$$

wherein:

$$A=\frac{C_1^2}{C_2^2}+1 \tag{16}$$

$$B=\frac{2C_1C_2}{c_3^2}+\frac{2C_1dx_2}{C_3}+2dy_1 \tag{17}$$

$$C=\frac{C_2^2}{C_3^2}+\frac{2C_2dx_2}{C_3}+dx_2^2+dy_2^2-r_2^2 \tag{18}$$

Focus

Now the output is known as a function of the input. For the focus model in Figure 22 this output has to be translated to the movement of the top of the centre lever (point m of the coupling plane).

Formulas (19) and (20) will preform this translation.

$$x_m=x_2-x_c\cos(\alpha)+y_c\sin(\alpha) \tag{19}$$

$$y_m=y_2-y_c\cos(\alpha)+x_c\sin(\alpha) \tag{20}$$

wherein:

$$\alpha=-\arctan(\frac{y_c}{x_c})+\arctan(\frac{x_2+x_1}{y_2+y_1}) \tag{21}$$

When the focus lever of the manipulator is moved through its full range the top

of the centre lever will move according to Figure 23.
Figure 23 shows that besides the focus movement a not to be discarded movement in convergence direction is generated by the focus lever.

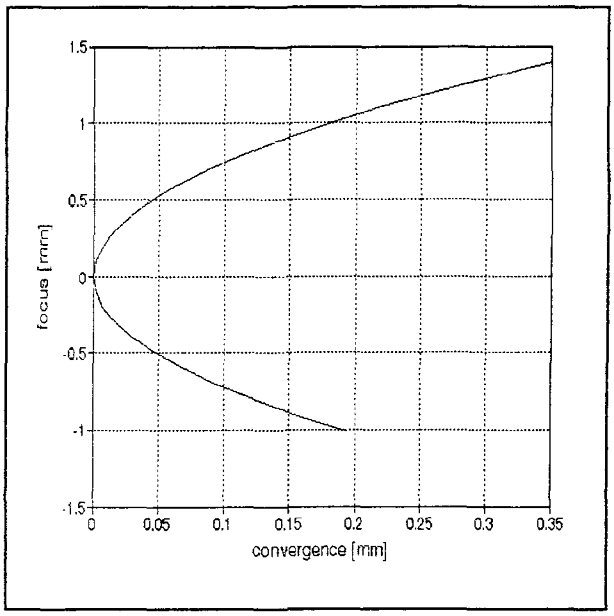


Figure 23: Movement of the top of the centre lever for movement of the focus lever

Convergence

The convergence mechanism consists of two identical four-bar-mechanisms (see Figure 24) which have the coupling plane attached at the output bar instead of the coupling bar as in the focus mechanism. This results in two formulas to calculate the movement of point m of the coupling plane. Formulas (22), (23) are valid for this translation.

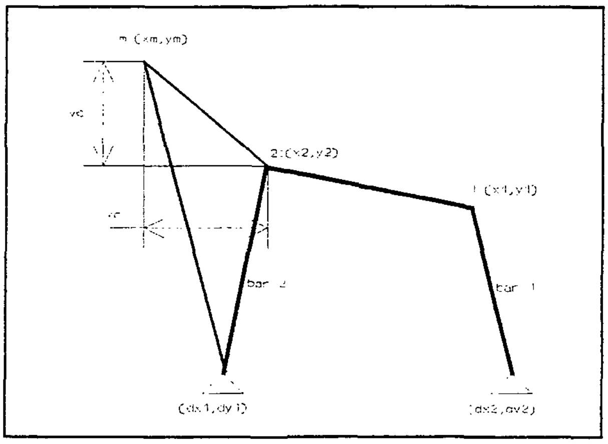


Figure 24: Four-bar-mechanism with coupling plane

$$x_m = x_2 - x_c\cos(\alpha) + y_c\sin(\alpha) \quad (22)$$

$$y_m = y_2 - y_c\cos(\alpha) + x_c\sin(\alpha) \quad (23)$$

wherein:

$$\alpha = -\arctan\left(\frac{y_c}{x_c}\right) + \arctan\left(\frac{x_2 + dxf}{y_2 + dyf}\right) \quad (24)$$

The output of the right four-bar-mechanism is the input for the left four-bar-mechanism in Figure 21. The output of these two four-bar-mechanisms represents the movement of the centre lever of the manipulator. When the convergence lever of the manipulator is moved through its full range the top of the centre lever will move according to Figure 25. Figure 25 shows that the focus movement caused by the convergence lever is maximum 9 μm so it has no visible influence on the focus of the picture.

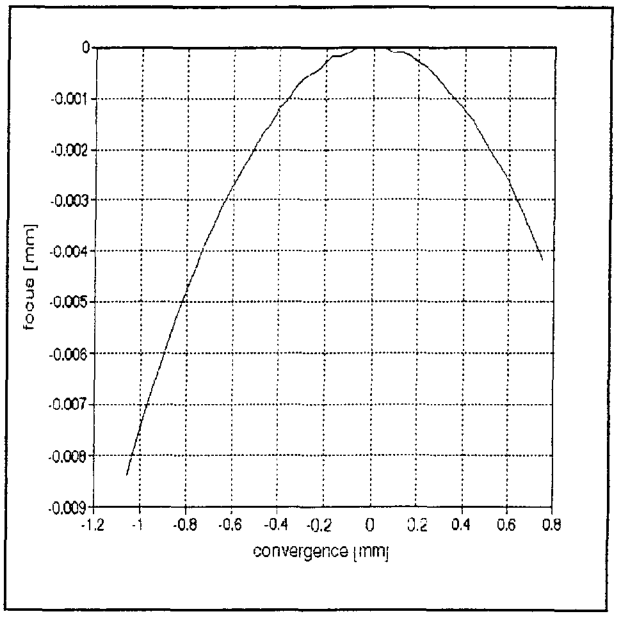


Figure 25: Movement of the top of the centre lever for movement of the convergence lever

By splitting up the manipulator into two separate models the interdependence of the two models is lost. Point (x1,y1) in the focus model is the same as point (dx2,dy2) in the convergence model. The interdependence is brought back by using the position of point (x1,y1) from the focus model as input for the position of point (dx2,dy2) in the convergence model.

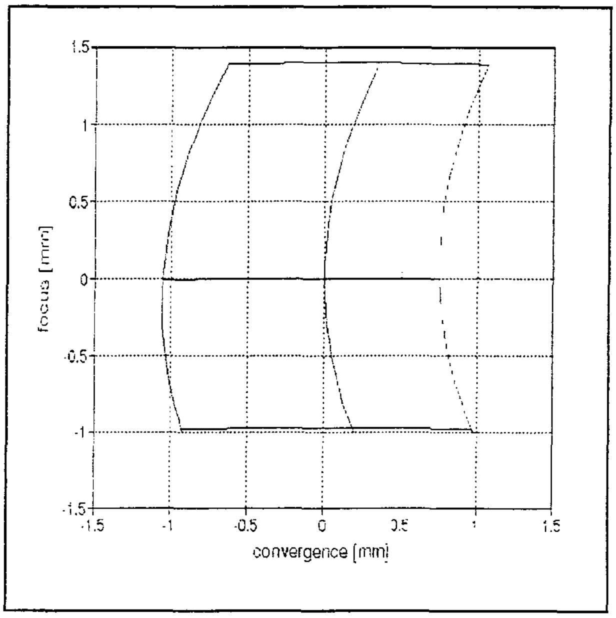


Figure 26: Range of points that can be reached by the top of the centre lever of the manipulator

An accurate model of the manipulator arises when the focus model and the convergence model are connected in this way. Both models are translated into a Pascal computer program and connected as stated above.

This has resulted in the first accurate model of manipulator that calculates the movement of the top of the centre lever as function of the position of the focus and convergence lever. Figure 26 shows the complete range of position that the top of the centre lever is able to reach.

This paragraph has shown that the manipulator according to this design is dependent and interdependent for focus and convergence adjustment instead of independent.

6.4 Model of LCD positioning system

Figure 27 shows the actual design of the positioning system. This design differs in one point from the original model. In the original model the attachment of the manipulators is situated at the edge of the active part of the LCD. In the actual design the manipulators are placed outside the active part of the LCD.

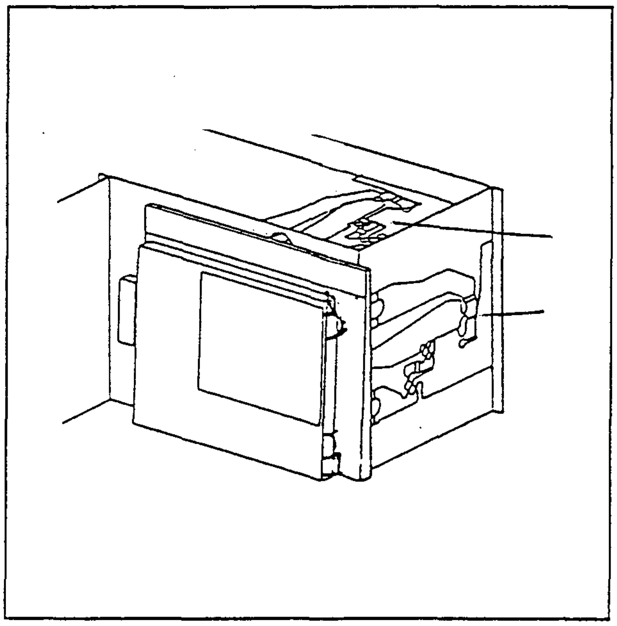


Figure 27: The LCD adjustment system

Consequences for the focus action

The above mentioned deviation from the original model influences the independence of the positioning. In Figure 28, Figure 29 and Figure 30 is represented how the LCD moves for a movement of the manipulator in focus direction.

As the figures show each movement causes the LCD to rotate around an axis through the other two manipulators. These rotations cause the LCD not only to

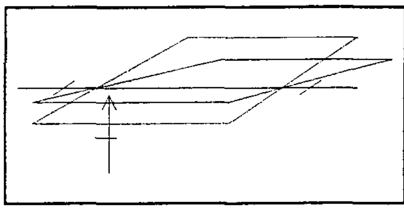


Figure 28:Side focus action

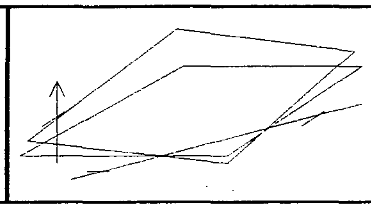


Figure 30: Top focus action

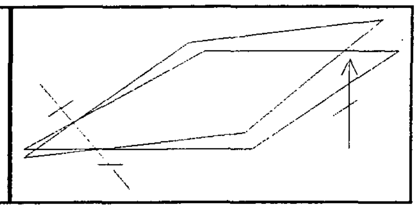


Figure 29: Bottom focus action

focus but also to converge. Figure 31 shows a side view of a rotation. The convergence shift can be calculated with:

$$x_p = r_p(1 - \cos(\arctan(\frac{y_m}{r_m}))) \tag{25}$$

In worst case situations this unwanted convergence shift is 19 μm and may be discarded. A not to be discarded convergence shift is introduced by the fact that the LCD lies above the plane shown in Figure 17 (see Figure 32). This causes a convergence shift of:

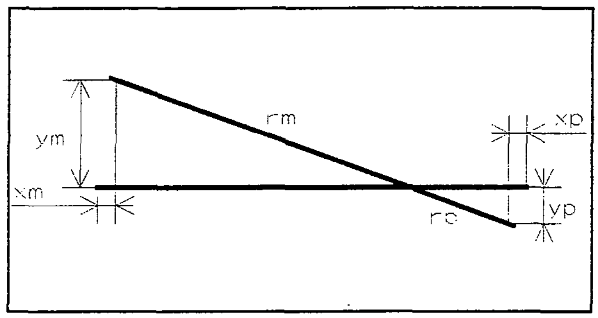


Figure 31: Side view of rotation of LCD in plane of manipulators

$$x_p = h * \frac{y_m}{r_m} \tag{26}$$

The problem with both described convergence shifts is that the image of the LCD will appear smaller on the screen because the projected plane of the LCD has become smaller.

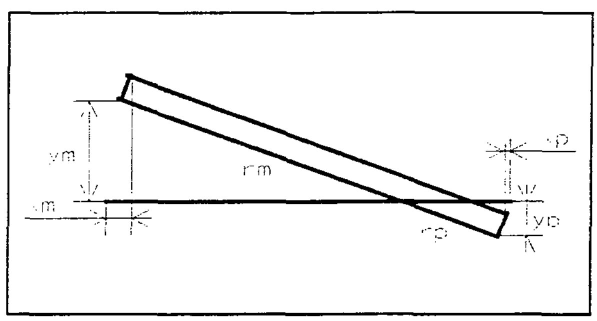


Figure 32: Convergence shift for LCD above the manipulator plane

Consequences for the convergence action

In the original model the convergence task is described as an independent procedure. This is only correct for very small movements, many times smaller than necessary for the actual convergence task. Figure 34 and Figure 35 show the rotation points (X) for movement of the manipulator in convergence direction. The rotation points are situated at the intersection of the lines through the manipulators which are not being manipulated. In the original model these points are believed to be stationary during the movement of the manipulator.

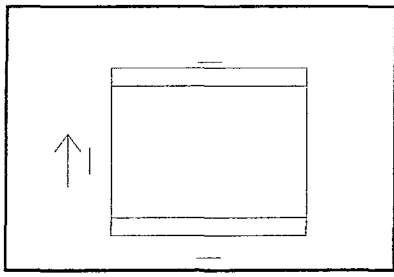


Figure 33:
Side convergence action

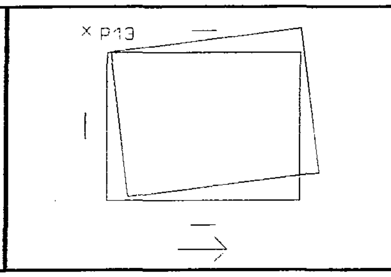


Figure 34:
Bottom convergence action

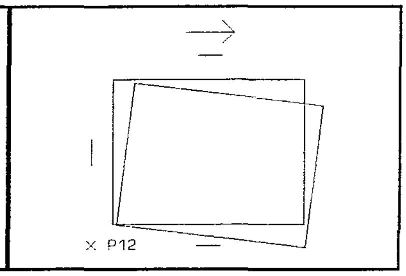


Figure 35:
Top convergence action

This is not the case because the two manipulators which are not being manipulated are forced to move by the manipulating action of the third manipulator. As a result of this the rotation point will be moved, so the LCD does not rotate around a stationary rotation point.
In the original model it was suggested to position one rotation point eg. P13 in Figure 34 first in x-direction and position the other rotation point (here P12 in Figure 35) by rotating around point P13. But when doing this the x-position (and y-position) of point P13 is changing so positioning has to be repeated.

When the five rotations and one translation (see Figure 28 to Figure 33) are correctly combined the actual movement of the LCD can be calculated.

In this paragraph it is shown that the original model of the LCD adjustment system (see paragraph 6.2) is not valid for the actual adjustment system. It also has been shown that the deviation of the model has introduced a dependence of focus and convergence adjustment.

6.5 Calculation of the adjustment range of the LCD

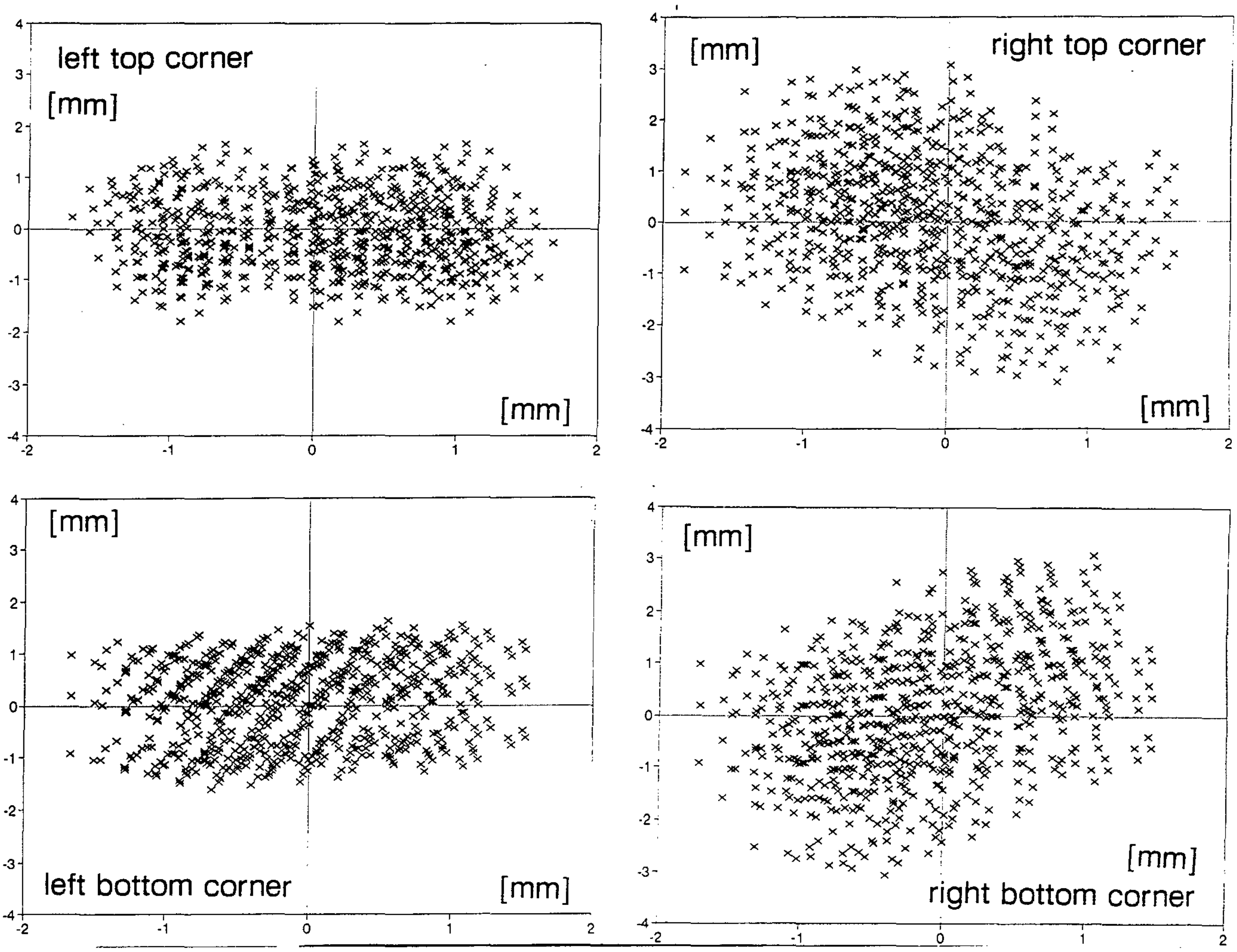


Figure 36: Adjustment ranges for each corner of the red LCD

A computer program has been written to calculate the adjustment range of the LCDs. The model of the manipulator as presented in paragraph 6.2 and the adjustment system discussed in paragraph 6.3 are combined in this computer program (see Appendix H).

Figure 36 shows the calculated adjustment range of the four corners of the red LCD.

As explained in paragraphs 6.2 and 6.3 the adjustment of focus and convergence are dependent. Due to this dependence the best focus adjustment position does not coincide with the best convergence adjustment position.

For production it is useful to know what the convergence adjustment range is, independent from focus adjustment. Due to the dependence this will result in a worst case situation of the convergence adjustment range. This worst case situation can be calculated as follows. Form all corners the smallest maximum convergence shift in each direction is taken. Then the convergence downwards and to the right are reduced by the dependence of the convergence from focus adjustment as shown in Figure 23 paragraph 6.2. This results in the worst case convergence adjustment range as shown in Figure 37

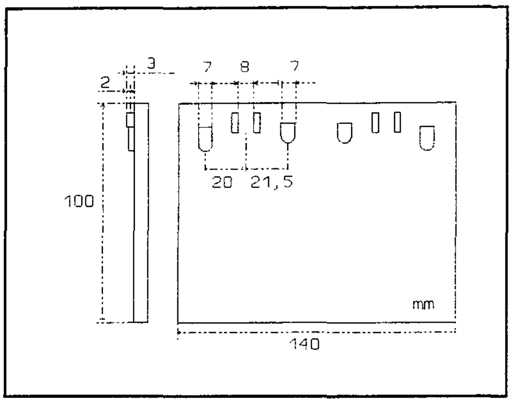


Figure 38: Testing gauge for manipulators

up:	1,4721	mm	≙	15 pixels
down:	1,3151	mm	≙	13 pixels
right:	1,2869	mm	≙	10 pixels
left:	1,6108	mm	≙	12 pixels

Figure 37: Worst case convergence adjustment range of red LCD

The collected data (see Appendix I) has also been fed into the computer model. This resulted in different convergence and focus shifts than the collected data showed.
This can only be explained by the use of bad parts. In this case the manipulators and the recohouses were suspected to be out of specification. Measurement by quality control confirmed this for the recohouses. For the manipulators a special testing gauge shown in Figure 38 has been made. Also this gauge confirmed that many of the manipulators were out of specification.

This together with the problem found in paragraph 6.1 are the main reasons why the adjustment range seemed to small. Another reason which often occurs that makes the adjustment range looks too small is the back to front mounting of the mirrors inside the recohouse.

7 Conclusions and recommendations

The adjustment of the LCDs is the main problem for production in the clean room. This problem is caused by the design of the adjustment mechanism. Instead of an independent adjustment procedure for focus and convergence the adjustment procedure is completely dependent.
The original independent adjustment procedure could not and can not be used because the points that are ment to be reference points for adjusting are not visible in the projected picture. In fact the reference points lie outside the active part of the LCD so they are not visible at all.

As a result of the dependent adjustment procedure the adjustment is highly dependent on the skills of the operator. Efficiency and quality is lost as a result of this dependence. With the present system it is virtually impossible to adjust the LCD to the best position.

At this moment only one operator is able to adjust the LCDs as efficient as possible with accepted quality. Therefore I recommend to train at least two other operators for this task. I do think that a new operator with a mathematical insight is able to preform the adjustment procedure within 5 to 10 minutes after a training on 50 sets.

A better solution would be to preform this adjustment task automatically. With a minor change in the program to compute the adjustment range it is possible use this program for automatic adjustment. Unfortunately it is most certainly too expensive to build an automatic adjustment station because the expected production quantities are to little.

The inspection criterium at the recohouse adjustment station can be enlarged from 4 to 7 pixels.

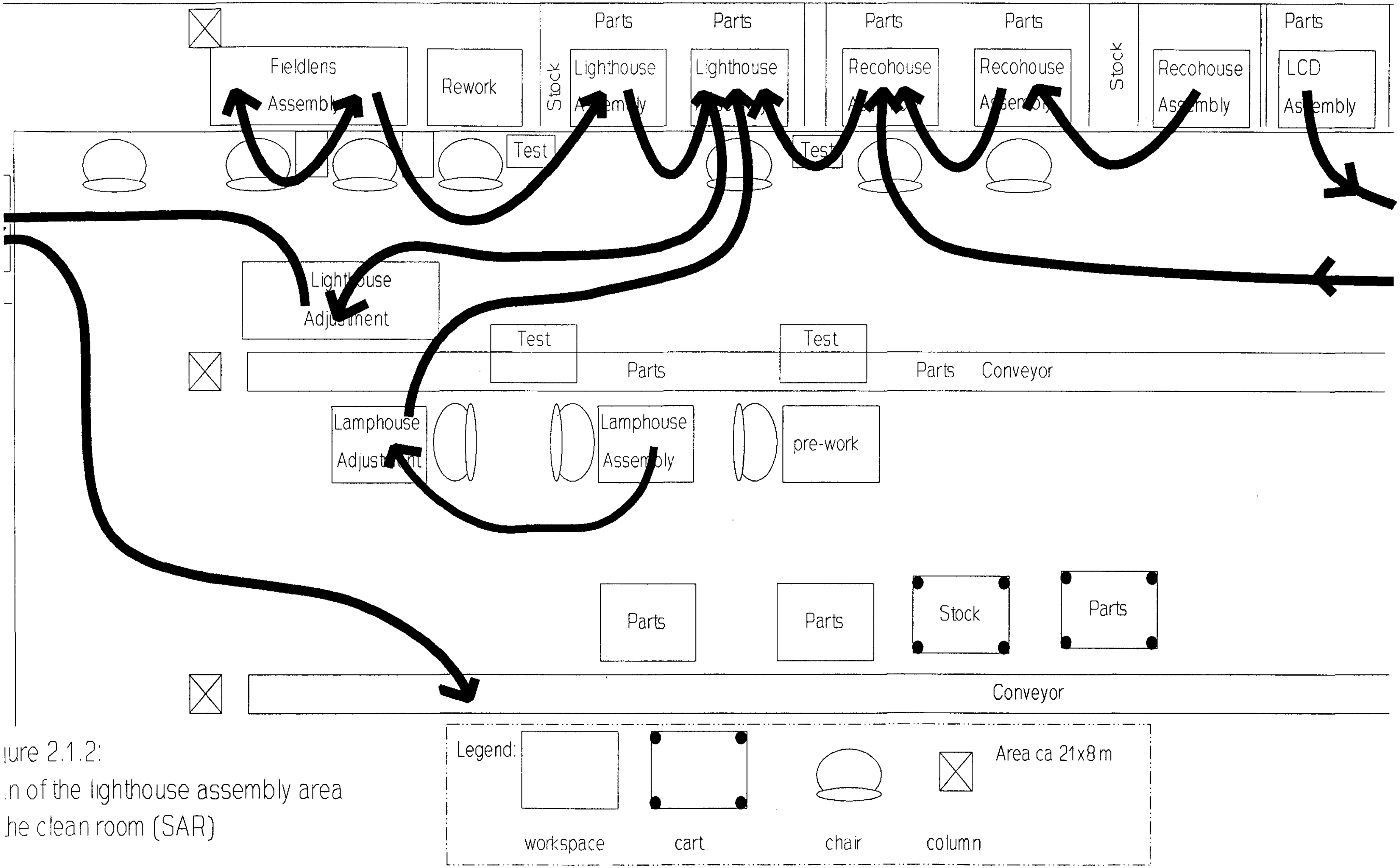
I propose the following improvements in the production process in the clean room. All these improvements are most certainly economically feasible.

	Problem	Solution	Introduction
1 -	Stock control	Report rejected parts	introduced
2 -	Incoming inspection	Gauge in production	introduced
3 -	Transportation damage	Damping material	not yet
4 -	Motivation personnel	Training	introduced
5 -	Saw cut head screw	Torx head screw	not yet
6 -	Handle of screwdriver	Thicker handle	not yet
7 -	ESD clip	Other clip	not yet
8 -	LCD inspection	New station	busy
9 -	Insulating ring	Chamfer on ring	not feasible
10 -	Lamphouse pins	Chamfer on pin	not yet
11 -	Vacuum system	Thicker hoses	not yet
12 -	Tap lock	New system	not yet
13 -	Clamp recohouse top	New mirror clamp	probably not
14 -	Clamp recohouse bottom	New mirror clamp	busy
15 -	Lamphouse adjustment	Installing cameras	probably not
16 -	Foam strip	Stick on top and bottom	introduced
17 -	Mounting top plate	New mirror clamp	busy
18 -	Foam ring	Foam strip	not yet
19 -	LCD adjustment	Installing cameras	busy
20 -	Dustcaps	New dustcaps	not yet
21 -	Screwdriver storage	Hooks on table	introduced
22 -	Adjustment range	New manipulator	introduced

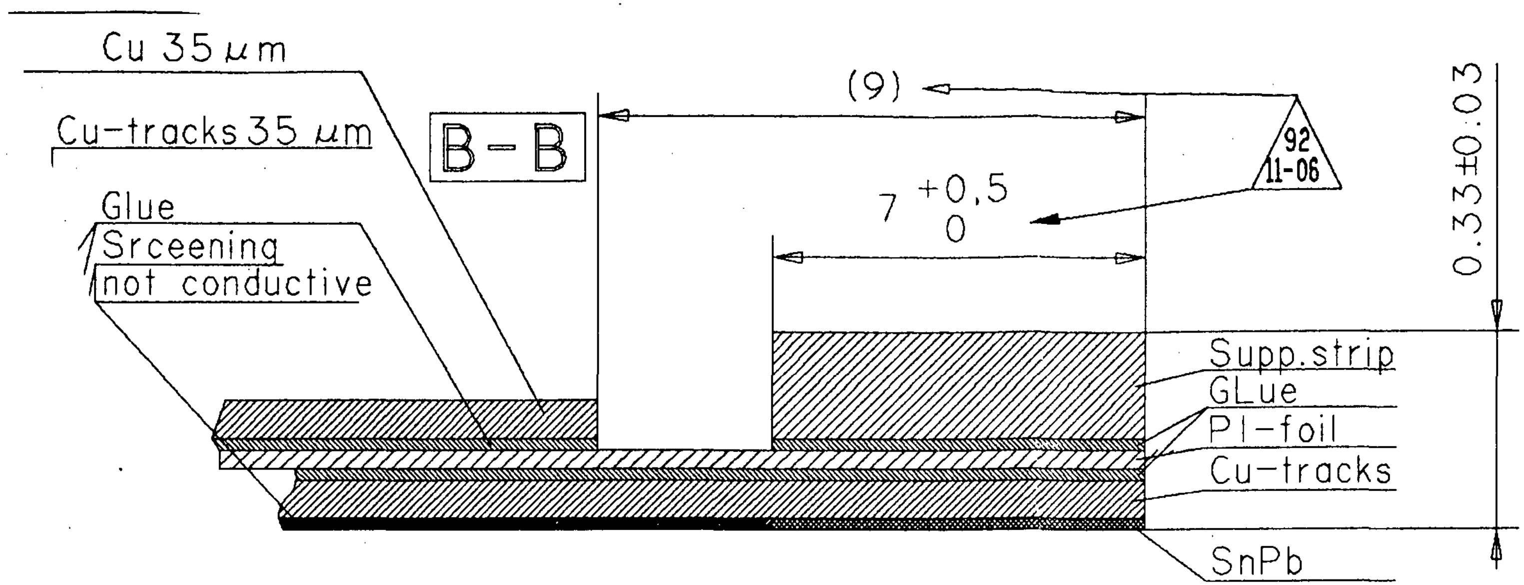
The later introduced carrying handle on the projector reduced the brake distance because the height of the projector is increased by including the carrying handle on the projector. This problem has been solved by increasing the height of the box.

Literature

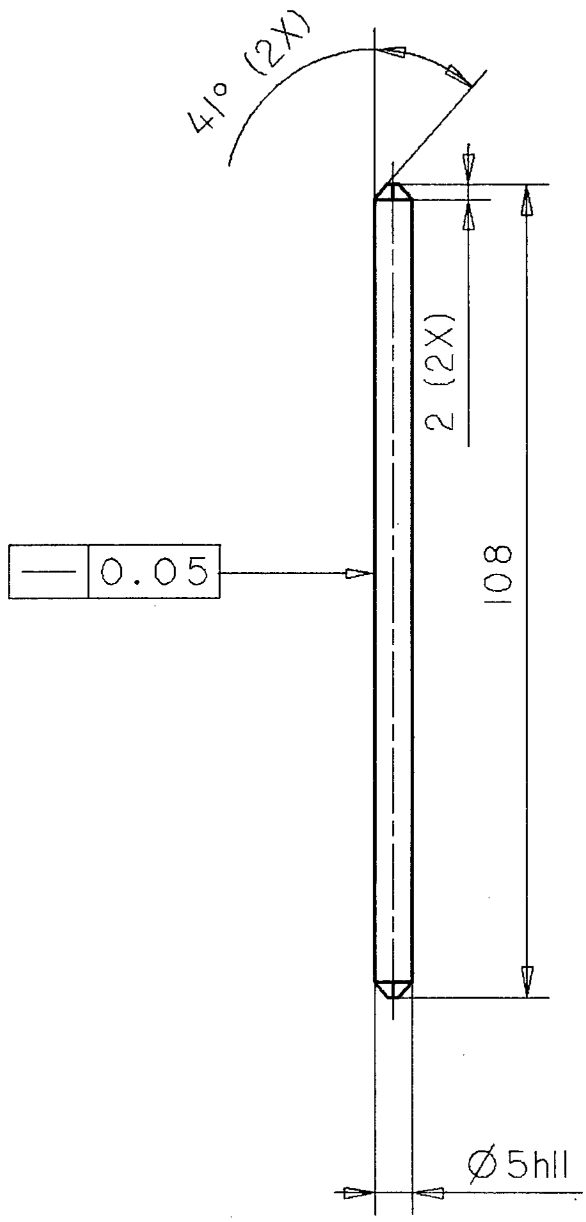
Koster, M.P., Constructieprincipes, Bedoeld voor het nauwkeurig bewegen en positioneren. Technische universiteit Eindhoven, Eindhoven 1990.



ıure 2.1.2:
.n of the lighthouse assembly area
he clean room (SAR)



Cu 35 µm
Cu-tracks 35 µm
Glue
Srceening
not conductive
B-B
(9)
7 +0,5 0
92
11-06
0.33±0.03
Supp.strip
GLue
PI-foil
Cu-tracks
SnPb



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UNIT EENHEID: mm

GENERAL ROUGHNESS ALGEMENE RUWHEID: Ra in um, UN-D 28

TOLERANCES UNLESS OTHERWISE STATED
TOLERANTIES TENZIJ ANDERS VERMELD

DIMENSIONS MAAT ±0.2 ANGLE HOEK ±2

SCALE SCHAAL 1:1 PROJ. EUROP.

UN-D 603

MATERIAL MATERIAAL: X10CrNiS18 9 230HV Un-N284

TREATMENT BEHANDELING: Degreased

MIRROR PIN

8222.671.6085

NAME NAAM M Ubbens

CHECK CONTR.

SUPERS. VERV.

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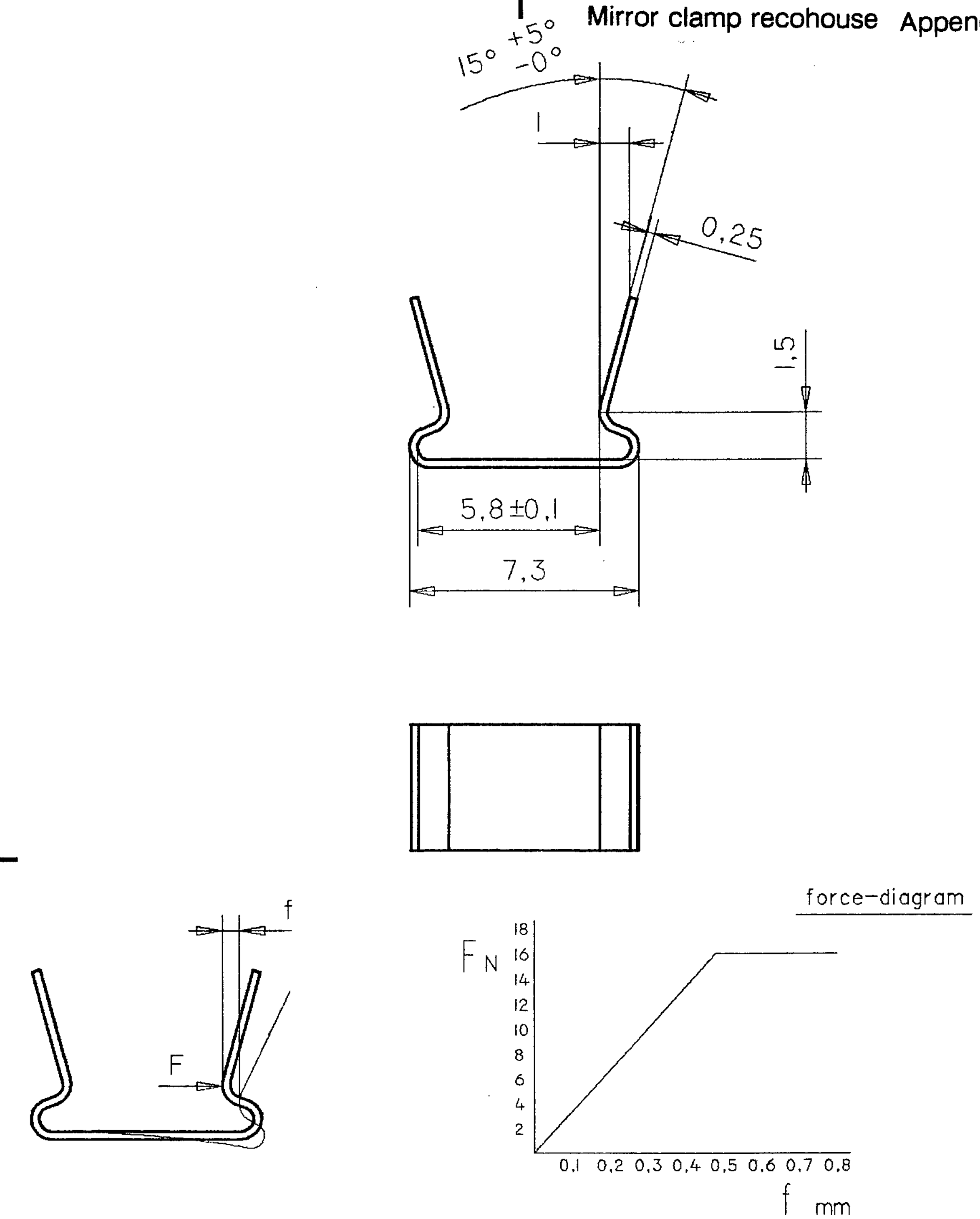

CHN:

UN-D 28 . . Ra in um

TOLERANCES UNLESS OTHERWISE STATED
TOLERANTIES TENZIJ ANDERS VERMELD

DIMENSIONS MAAT ±0.2 — ANGLE HOEK ±2°

UN-D 603

ITEM POSNR | ASSEMBLY NO. SAMENSTELLINGSNR. | QUANT. AANTAL

GENERAL ROUGHNESS ALGEMENE RUWHEID | UNIT EENHEID mm | MATERIAL MATERIAAL: CuSn8 220HV UN-R154

PATTERN NO. / MODELNR.

SCALE SCHAAL 5 : 1 | PROJ. EUROP. | TREATMENT BEHANDELING

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CLASS NO.

MIRROR CLAMP

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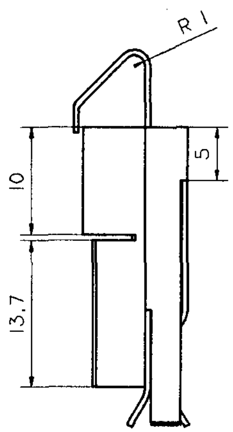
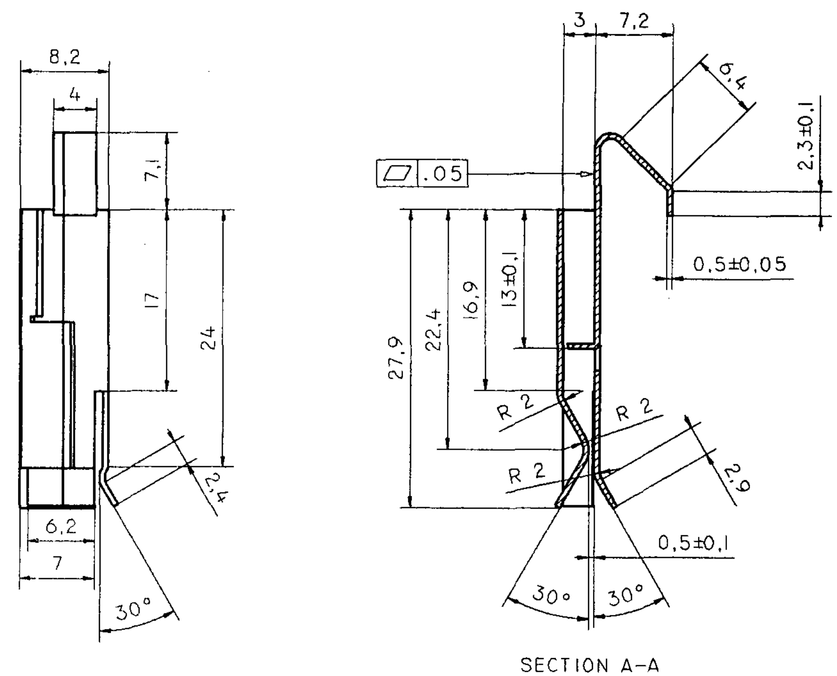
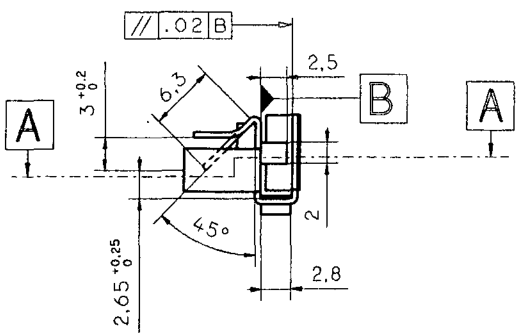
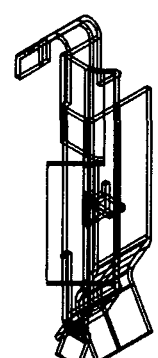
8222 285 13060



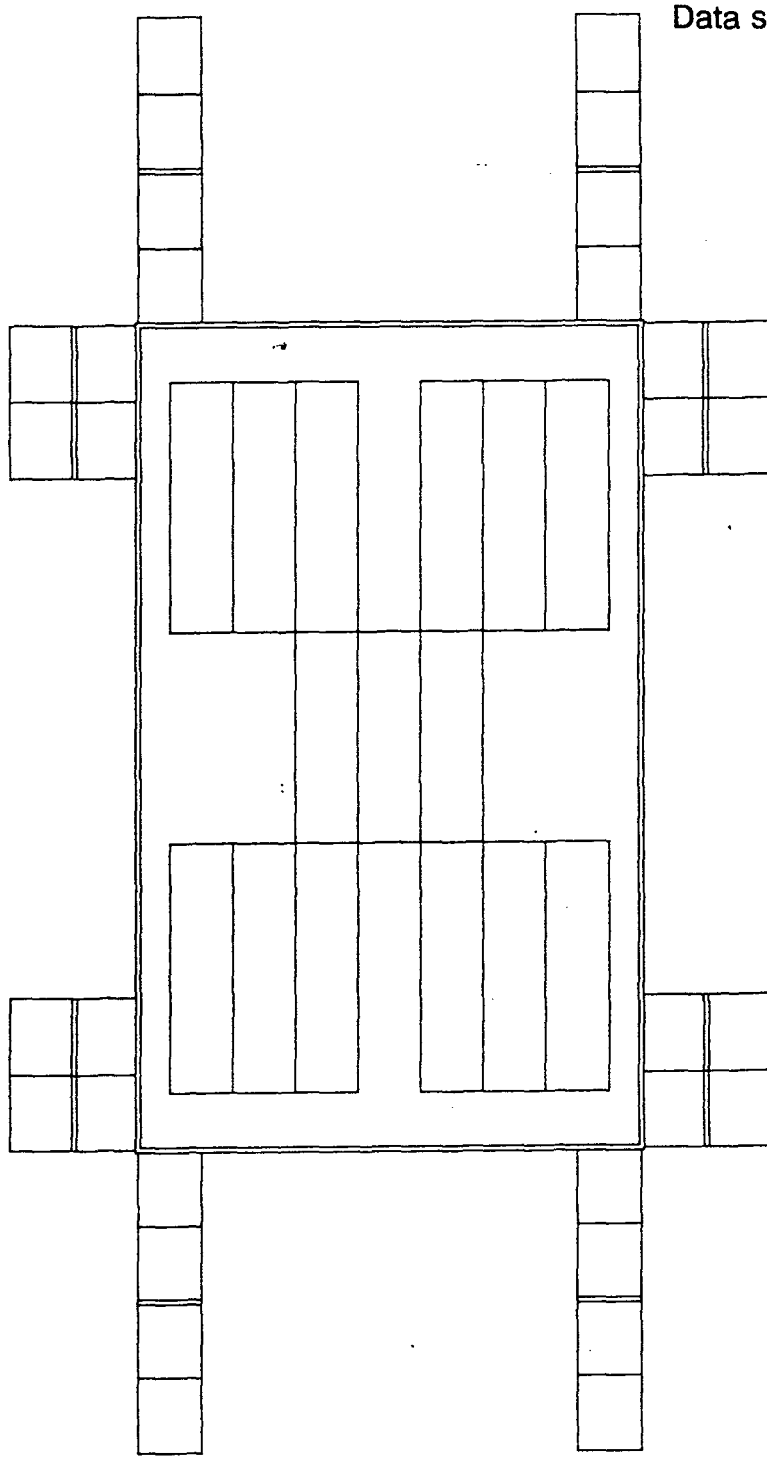




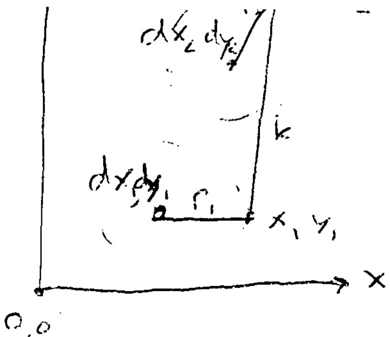


Bending radii 0.1 mm on inner side
unless otherwise stated

CHN:		
UNIT / EENHEID: mm	GENERAL ROUGHNESS / ALGEMENE RUWHEID: Ra in µm, UN-D 28	MATERIAL / MATERIAAL: CuZn15 acc to R153
SCALE / SCHAAL: 2 : 1	PROJ. EUROP.	TOLERANCES UNLESS OTHERWISE STATED / TOLERANTIES TENZIJ ANDERS VERMELD: DIMENSIONS / MAAT ± 0.2; ANGLE / HOEK ± 2°; UN-D 603
TREATMENT / BEHANDELING:		
Mirror clamp		8222 671 6079
NAME / NAAM: M. Ubbens	SUPERS. / VERV.:	01 | 10 | 110 – 01
CHECK / CONTR.:	DAT 93-11-25	© PHILIPS CONSUMER ELECTRONICS B.V.



...rule : $(x_2 + \Delta x_2)^2 + (y_2 + \Delta y_2)^2 = r_2^2$ (2)



$$x^2 - 2xx_1 + x_1^2 + y^2 - 2yy_1 + y_1^2 = l_c^2$$

$$x^2 + 2x\,dx + dx^2 + y^2 + 2y\,dy + dy^2 = r^2 \quad -$$

$$-2xx_1 + x_1^2 - 2yy_1 + y_1^2 - 2x\,dx - dx^2 - 2y\,dy - dy^2 = l_c^2 - r^2$$

$$-2x(x_1 + dx) = k^2 - r^2 - x_1^2 - y_1^2 + 2y(y_1 + dy) + dy^2 + dx^2$$

$$x = \frac{2y(y_1 + dy) + k^2 - r^2 - x_1^2 - y_1^2 + dy^2 + dx^2}{-2(x_1 + dx)} = \frac{yC_1 + C_2}{C_3}$$

met $C_1 = 2(y_1 + dy)$

$C_2 = k^2 - r^2 - x_1^2 - y_1^2 + dy^2 + dx^2$

$C_3 = -2(x_1 + dx)$

x in (2)

$$\left(\frac{yC_1 + C_2}{C_3}\right)^2 + 2\left(\frac{yC_1 + C_2}{C_3}\right)dx + dx^2 + y^2 + 2y\,dy + dy^2 = r^2$$

$$\frac{y^2C_1^2}{C_3^2} + \frac{2yC_1C_2}{C_3^2} + \frac{C_2^2}{C_3^2} + \frac{2yC_1\,dx}{C_3} + \frac{2C_2\,dx}{C_3} + dx^2 + y^2 + 2y\,dy + dy^2 - r^2 = 0$$

$$\underbrace{y^2\left(\frac{C_1^2}{C_3^2} + 1\right)}_{A} + \underbrace{y\left(\frac{2C_1C_2}{C_3^2} + \frac{2C_1\,dx}{C_3} + 2\,dy\right)}_{B} + \underbrace{\left(\frac{C_2^2}{C_3^2} + \frac{2C_2\,dx}{C_3} + dx^2 + dy^2 - r^2\right)}_{C} = 0$$

```
program manipulator;
uses graph;
var driver, modus: integer;
var edge: text;
var filename: string[14];
var ch: char;
var x1,y1,dx1,dy1,x2,y2,dx2,dy2,r1,r2,k,t: real;
var hm,hf,hc,dxf,dyf,xm,ym,tx,ty,h,w: real;
var h1,h2,h3,h4: real;
var stop: integer;
var hlt, hrt, hlb, hrb, hmt, hms, hmb: real;
var hfs, hcs, hfb, hcb, hft, hct: real;
var xlt, ylt, zlt, xrt, yrt, zrt: real;
var xlb, ylb, zlb, xrb, yrb, zrb: real;
var sdxlt, sdylt, sdzlt, sdxrt, sdyrt, sdzrt: real;
var sdxlb, sdylb, sdzlb, sdxrb, sdyrb, sdzrb: real;
var sfxlt, sfylt, sfzlt, sfxrt, sfyrt, sfzrt: real;
var sfxlb, sfylb, sfzlb, sfxrb, sfyrb, sfzrb: real;
var dxlt, dylt, dzlt, dxrt, dyrt, dzrt: real;
var dxlb, dylb, dzlb, dxrb, dyrb, dzrb: real;
var bdxlt, bdylt, bdzlt, bdxrt, bdyrt, bdzrt: real;
var bdxlb, bdylb, bdzlb, bdxrb, bdyrb, bdzrb: real;
var tdxlt, tdylt, tdzlt, tdxrt, tdyrt, tdzrt: real;
var tdxlb, tdylb, tdzlb, tdxrb, tdyrb, tdzrb: real;
var bfxlt, bfylt, bfzlt, bfxrt, bfyrt, bfzrt: real;
var bfxlb, bfylb, bfzlb, bfxrb, bfyrb, bfzrb: real;
var tfxlt, tfylt, tfzlt, tfxrt, tfyrt, tfzrt: real;
var tfxlb, tfylb, tfzlb, tfxrb, tfyrb, tfzrb: real;
var bdxmt, bdymt, bdxms, bdyms, bdxmb, bdymb: real;
var tdxmt, tdymt, tdxms, tdyms, tdxmb, tdymb: real;
var bfxmt, bfymt, bfxms, bfyms, bfxmb, bfymb: real;
var tfxmt, tfymt, tfxms, tfyms, tfxmb, tfymb: real;
var dxmt, dymt, dzmt, dxms, dyms, dzms, dxmb, dymb, dzmb: real;
var rlt, rrt, rlb, rrb, rm, rmt, rms, rmb: real;
var irt, irb: real;

function afronden(q: real): real;
begin
     afronden:=round(q*1e8)*1e-8;
end;

function radius(xp,yp: real): real;
var x,y: real;
begin
     x:=tx*(ty*yp+tx*xp-ty*ty)/(ty*ty+tx*tx);
     y:=ty/tx*x+ty;
     radius:=sqrt(sqr(x-xp)+sqr(y-yp));
end;

procedure lever;
var c1,c2,c3: real;
var a, b, c: real;
begin
     a:=0; b:=0; c:=0; c1:=0; c2:=0; c3:=0;
     c1:=2*(dy2+y1);
     c2:=-sqr(x1)-sqr(y1)-sqr(r2)+sqr(k)+sqr(dx2)+sqr(dy2);
     c3:=-2*(x1+dx2);
     a:=sqr(c1/c3)+1;
```

```
     b:=2*c1*c2/sqr(c3)+2*dx2*c1/c3+2*dy2;
     c:=sqr(c2/c3)+2*dx2*c2/c3+sqr(dx2)+sqr(dy2)-sqr(r2);
     y2:=(-b+sqrt(sqr(b)-4*a*c))/(2*a);
     x2:=(y2*c1+c2)/c3;
end;

procedure focus;
begin
     dx1:=10; dy1:=-67; r1:=10; dx2:=-10.5; dy2:=42; r2:=5; k:=sqrt(655.25);
     x1:=dx1+r1*cos(hf);
     y1:=dy1+r1*sin(hf);
     lever;
     t:=-arctan(5.5/25)+arctan((x2-x1)/(y2-y1));
     xm:=x2-5.5*cos(t)+42*sin(t);
     ym:=y2+42*cos(t)+5.5*sin(t);
end;

procedure convergence;
begin
     dx1:=22; dy1:=-37; r1:=5; dx2:=-10.5; dy2:=46; r2:=sqrt(232); k:=5.5;
     x1:=dx1+r1*-sin(hc);
     y1:=dy1+r1*cos(hc);
     lever;
     t:=arctan((y2+dy2)/(x2+dx2))+arctan(6/14)-pi/2;
     dx1:=10.5; dy1:=-46; r1:=4; dx2:=dxf; dy2:=dyf; r2:=sqrt(655.25); k:=5;
     x1:=dx1+r1*-sin(t);
     y1:=dy1+r1*cos(t);
     lever;
     t:=-arctan(5.5/25)+arctan((x2+dxf)/(y2+dyf));
     xm:=x2-5.5*cos(t)+42*sin(t);
     ym:=y2+42*cos(t)+5.5*sin(t);
     write(' X     ',xm:8:6);
     writeln(' Y     ',ym:8:6);
end;


procedure conv_side;
begin
{     writeln('Convergence side');}
     sdxlt:=0; sdylt:=xm; sdzlt:=0;
     sdxrt:=0; sdyrt:=xm; sdzrt:=0;
     sdxlb:=0; sdylb:=xm; sdzlb:=0;
     sdxrb:=0; sdyrb:=xm; sdzrb:=0;
end;

procedure conv_bottom;
begin
{     writeln('Convergence bottom');}

     rlt:=0; hlt:=0;
     rrt:=0; hrt:=0;
     rlb:=0; hlb:=0;
     rrb:=0; hrb:=0;
     rmt:=0; hmt:=0;
     rms:=0; hms:=0;
     rm:=0;  hm :=0;

     dxlt:=0; dylt:=0;
```

```
    dxrt:=0; dyrt:=0;
    dxlb:=0; dylb:=0;
    dxrb:=0; dyrb:=0;
    dxmt:=0; dymt:=0;
    dxms:=0; dyms:=0;
             dymb:=0;

    bdxlt:=0; bdylt:=0;
    bdxrt:=0; bdyrt:=0;
    bdxlb:=0; bdylb:=0;
    bdxrb:=0; bdyrb:=0;
    bdxmt:=0; bdymt:=0;
    bdxms:=0; bdyms:=0;
    bdxmb:=0; bdymb:=0;

    stop:=0;

    xm:=xm/100;

    xm:=afronden(xm);

    while stop <= 100 do
    begin

{         write(stop);
         if stop=100 then writeln;  }

         rlt:=sqrt(sqr(tx-w+bdxlt-bdxms)+sqr(ty-h-bdylt+bdymt));
         rrt:=sqrt(sqr(tx+w+bdxrt-bdxms)+sqr(ty-h-bdyrt+bdymt));
         rlb:=sqrt(sqr(tx-w+bdxlb-bdxms)+sqr(ty+h-bdylb+bdymt));
         rrb:=sqrt(sqr(tx+w+bdxrb-bdxms)+sqr(ty+h-bdyrb+bdymt));
         rmt:=sqrt(sqr(tx  +bdxmt-bdxms)+sqr(          bdymt));
         rms:=sqrt(sqr(          -bdxms)+sqr(ty  -bdyms+bdymt));
         rm :=sqrt(sqr(tx  +bdxmb-bdxms)+sqr(2*ty-bdymb+bdymt));

         dymb:=2*ty-bdymb+bdymt-sqrt(sqr(rm)-sqr(tx+bdxmb-bdxms+xm));
         dymb:=afronden(dymb);
         hm:=sqrt(sqr(xm)+sqr(dymb))/rm;
         if xm>0 then hm:=-hm;

         hlt:=arctan((tx-w+bdxlt-bdxms)/(ty-h-bdylt+bdymt));
         hrt:=arctan((tx+w+bdxrt-bdxms)/(ty-h-bdyrt+bdymt));
         hlb:=arctan((tx-w+bdxlb-bdxms)/(ty+h-bdylb+bdymt));
         hrb:=arctan((tx+w+bdxrb-bdxms)/(ty+h-bdyrb+bdymt));
         if bdymt <> 0 then
         hmt:=arctan((tx  +bdxmt-bdxms)/(          bdymt));
         hms:=arctan((          -bdxms)/(ty  -bdyms+bdymt));

         dxlt:=rlt*(sin(hm+hlt)-sin(hlt)); dylt:=rlt*(-cos(hm+hlt)+cos(hlt));
         dxrt:=rrt*(sin(hm+hrt)-sin(hrt)); dyrt:=rrt*(-cos(hm+hrt)+cos(hrt));
         dxlb:=rlb*(sin(hm+hlb)-sin(hlb)); dylb:=rlb*(-cos(hm+hlb)+cos(hlb));
         dxrb:=rrb*(sin(hm+hrb)-sin(hrb)); dyrb:=rrb*(-cos(hm+hrb)+cos(hrb));
         dxmt:=rmt*(sin(hm+hmt)-sin(hmt)); dymt:=rmt*(-cos(hm+hmt)+cos(hmt));
         dxms:=rms*(sin(hm+hms)-sin(hms)); dyms:=rms*(-cos(hm+hms)+cos(hms));

         bdxlt:=bdxlt+dxlt; bdylt:=bdylt+dylt;
         bdxrt:=bdxrt+dxrt; bdyrt:=bdyrt+dyrt;
         bdxlb:=bdxlb+dxlb; bdylb:=bdylb+dylb;
```

```
        bdxrb:=bdxrb+dxrb; bdyrb:=bdyrb+dyrb;
        bdxmt:=bdxmt+dxmt; bdymt:=bdymt+dymt;
        bdxms:=bdxms+dxms; bdyms:=bdyms+dyms;
        bdxmb:=bdxmb+ xm ; bdymb:=bdymb+dymb;

        stop:=stop+1;
    end;
end;

procedure conv_top;
begin
{     writeln('Convergence top');}

    rlt:=0;
    rrt:=0;
    rlb:=0;
    rrb:=0;
    rmb:=0;
    rms:=0;
    rm:=0;
    hm:=0;

    dxlt:=0; dylt:=0;
    dxrt:=0; dyrt:=0;
    dxlb:=0; dylb:=0;
    dxrb:=0; dyrb:=0;
    dxmb:=0; dymb:=0;
    dxms:=0; dyms:=0;

    tdxlt:=0; tdylt:=0;
    tdxrt:=0; tdyrt:=0;
    tdxlb:=0; tdylb:=0;
    tdxrb:=0; tdyrb:=0;
    tdxmb:=0; tdymb:=0;
    tdxms:=0; tdyms:=0;
    tdxmt:=0; tdymt:=0;

    stop:=0;

    xm:=xm/100;
    xm:=afronden(xm);

    while stop <= 100 do

    begin

{          write(stop);
        if stop=100 then writeln; }

        rlb:=sqrt(sqr(tx-w+tdxlb-tdxms+bdxlb-bdxms)+sqr(ty-h-tdylb+tdymb-bdylb+bdymt));
        rrb:=sqrt(sqr(tx+w+tdxrb-tdxms+bdxrb-bdxms)+sqr(ty-h-tdyrb+tdymb-bdyrb+bdymt));
        rlt:=sqrt(sqr(tx-w+tdxlt-tdxms+bdxlt-bdxms)+sqr(ty+h-tdylt+tdymb-bdylt+bdymt));
        rrt:=sqrt(sqr(tx+w+tdxrt-tdxms+bdxrt-bdxms)+sqr(ty+h-tdyrt+tdymb-bdyrt+bdymt));
        rmb:=sqrt(sqr(tx  +tdxmb-tdxms+bdxmt-bdxms)+sqr(          tdymb      +bdymt));
        rms:=sqrt(sqr(          -tdxms      -bdxms)+sqr(ty  -tdyms+tdymb-bdyms+bdymt));
        rm :=sqrt(sqr(tx  +tdxmt-tdxms+bdxmb-bdxms)+sqr(2*ty-tdymt+tdymb-bdymb+bdymt));

        dymt:=2*ty-tdymt+tdymb-bdymb+bdymt-sqrt(sqr(rm)-sqr(tx+tdxmt-tdxms+bdxmb-bdxms+xm));
```

```
        dymt:=afronden(dymt);
        hm:=sqrt(sqr(xm)+sqr(dymt))/rm;
        if xm>0 then hm:=-hm;

        hlb:=arctan((tx-w+tdxlb-tdxms+bdxlb-bdxms)/(ty-h-tdylb+tdymb-bdylb+bdymt));
        hrb:=arctan((tx+w+tdxrb-tdxms+bdxrb-bdxms)/(ty-h-tdyrb+tdymb-bdyrb+bdymt));
        hlt:=arctan((tx-w+tdxlt-tdxms+bdxlt-bdxms)/(ty+h-tdylt+tdymb-bdylt+bdymt));
        hrt:=arctan((tx+w+tdxrt-tdxms+bdxrt-bdxms)/(ty+h-tdyrt+tdymb-bdyrt+bdymt));
        if tdymb+bdymt <> 0 then
        hmb:=arctan((tx  +tdxmb-tdxms+bdxmt-bdxms)/(          tdymb      +bdymt));
        hms:=arctan((          -tdxms      -bdxms)/(ty  -tdyms+tdymb-bdyms+bdymt));

        dxlt:=rlt*(sin(hm+hlt)-sin(hlt)); dylt:=rlt*(cos(hm+hlt)-cos(hlt));
        dxrt:=rrt*(sin(hm+hrt)-sin(hrt)); dyrt:=rrt*(cos(hm+hrt)-cos(hrt));
        dxlb:=rlb*(sin(hm+hlb)-sin(hlb)); dylb:=rlb*(cos(hm+hlb)-cos(hlb));
        dxrb:=rrb*(sin(hm+hrb)-sin(hrb)); dyrb:=rrb*(cos(hm+hrb)-cos(hrb));
        dxmb:=rmb*(sin(hm+hmb)-sin(hmb)); dymb:=rmb*(cos(hm+hmb)-cos(hmb));
        dxms:=rms*(sin(hm+hms)-sin(hms)); dyms:=rms*(cos(hm+hms)-cos(hms));

        tdxlt:=tdxlt+dxlt; tdylt:=tdylt+dylt;
        tdxrt:=tdxrt+dxrt; tdyrt:=tdyrt+dyrt;
        tdxlb:=tdxlb+dxlb; tdylb:=tdylb+dylb;
        tdxrb:=tdxrb+dxrb; tdyrb:=tdyrb+dyrb;
        tdxmb:=tdxmb+dxmb; tdymb:=tdymb+dymb;
        tdxms:=tdxms+dxms; tdyms:=tdyms+dyms;
        tdxmt:=tdxmt+ xm ; tdymt:=tdymt+dymt;

        stop:=stop+1;

    end;
end;

procedure focus_side;
var x: real;
begin
{    writeln('Focus side');}
    x:=0;
    if ym<>0 then
    x:=(1-cos(arctan(ym/sqrt(sqr(tx)-sqr(ym)))));
    sfxlt:= w*x+irt*ym/tx; sfylt:=0; sfzlt:= ym*w/tx+irt*x;
    sfxrt:=-w*x+irt*ym/tx; sfyrt:=0; sfzrt:=-ym*w/tx+irt*x;
    sfxlb:= w*x+irb*ym/tx; sfylb:=0; sfzlb:= ym*w/tx+irb*x;
    sfxrb:=-w*x+irb*ym/tx; sfyrb:=0; sfzrb:=-ym*w/tx+irb*x;
end;

procedure focus_bottom;
begin
{   writeln('Focus bottom');}
   rlb:=radius(-w,-h);
   rm:=radius(0,-ty);
   rlt:=radius(-w,h);
   rrb:=radius(w,-h);
   rrt:=radius(w,h);

   h2:=arctan(ym/rm);
   h3:=arctan(ty/tx);

   bfxlt:=( rlt*(1-cos(h2))-irt*ym/rm)*cos(h3);
```

```
    bfxrt:=(-rrt*(1-cos(h2))-irt*ym/rm)*cos(h3);
    bfxrb:=(-rrb*(1-cos(h2))-irb*ym/rm)*cos(h3);
    bfxlb:=(-rlb*(1-cos(h2))-irb*ym/rm)*cos(h3);

    bfylt:=(-rlt*(1-cos(h2))+irt*ym/rm)*sin(h3);
    bfyrt:=( rrt*(1-cos(h2))+irt*ym/rm)*sin(h3);
    bfyrb:=( rrb*(1-cos(h2))+irb*ym/rm)*sin(h3);
    bfylb:=( rlb*(1-cos(h2))+irb*ym/rm)*sin(h3);

    bfzlt:=-ym*rlt/rm+irt*(1-cos(h2));
    bfzrt:= ym*rrt/rm+irt*(1-cos(h2));
    bfzrb:= ym*rrb/rm+irb*(1-cos(h2));
    bfzlb:= ym*rlb/rm+irb*(1-cos(h2));

end;

procedure focus_top;
begin

{    writeln('Focus top');}

    rlt:=radius(-w,-h);
    rm:=radius(0,-ty);
    rlb:=radius(-w,h);
    rrt:=radius(w,-h);
    rrb:=radius(w,h);

    h2:=arctan(ym/rm);
    h3:=arctan(ty/tx);

    tfxlt:=(-rlt*(1-cos(h2))-irt*ym/rm)*cos(h3);
    tfxrt:=(-rrt*(1-cos(h2))-irt*ym/rm)*cos(h3);
    tfxrb:=(-rrb*(1-cos(h2))-irb*ym/rm)*cos(h3);
    tfxlb:=( rlb*(1-cos(h2))-irb*ym/rm)*cos(h3);

    tfylt:=(-rlt*(1-cos(h2))-irt*ym/rm)*sin(h3);
    tfyrt:=(-rrt*(1-cos(h2))-irt*ym/rm)*sin(h3);
    tfyrb:=(-rrb*(1-cos(h2))-irb*ym/rm)*sin(h3);
    tfylb:=( rlb*(1-cos(h2))-irb*ym/rm)*sin(h3);

    tfzlt:= ym*rlt/rm+irt*(1-cos(h2));
    tfzrt:= ym*rrt/rm+irt*(1-cos(h2));
    tfzrb:= ym*rrb/rm+irb*(1-cos(h2));
    tfzlb:=-ym*rlb/rm+irb*(1-cos(h2));

end;

procedure redlcd;
begin
{     writeln('Red LCD');   }
     w:=28.75; h:=21.4; tx:=42.57; ty:=38.2; irt:=12.04; irb:=9.8;
     xlt:=0; ylt:=0; zlt:=0;
     xrt:=0; yrt:=0; zrt:=0;
     xlb:=0; ylb:=0; zlb:=0;
     xrb:=0; yrb:=0; zrb:=0;

     hf:=hfs; hc:=hcs;
     focus;
```

```
     dxf:=-x1; dyf:=-y1;
     convergence;
     focus_side;
     conv_side;

     hf:=hfb; hc:=hcb;
     focus;
     dxf:=-x1; dyf:=-y1;
     convergence;
     focus_bottom;
     conv_bottom;

     hf:=hft; hc:=hct;
     focus;
     dxf:=-x1; dyf:=-y1;
     convergence;
     focus_top;
     conv_top;

     xlt:=sdxlt+bdxlt+tdxlt+sfxlt+bfxlt+tfxlt; ylt:=sdylt+bdylt+tdylt+sfylt+bfylt+tfylt;
        zlt:=sfzlt+bfzlt+tfzlt;
     xrt:=sdxrt+bdxrt+tdxrt+sfxrt+bfxrt+tfxrt; yrt:=sdyrt+bdyrt+tdyrt+sfyrt+bfyrt+tfyrt;
        zrt:=sfzrt+bfzrt+tfzrt;
     xlb:=sdxlb+bdxlb+tdxlb+sfxlb+bfxlb+tfxlb; ylb:=sdylb+bdylb+tdylb+sfylb+bfylb+tfylb;
        zrb:=sfzrb+bfzrb+tfzrb;
     xrb:=sdxrb+bdxrb+tdxrb+sfxrb+bfxrb+tfxrb; yrb:=sdyrb+bdyrb+tdyrb+sfyrb+bfyrb+tfyrb;
        zlb:=sfzlb+bfzlb+tfzlb;

end;

procedure store;
begin
     append(edge);
     writeln(edge,hf:5:4,' ',hc:5:4,' ',xm:5:4,' ',ym:5:4);
     {writeln(edge,hfs:5:4,' ',hcs:5:4,' ',hfb:5:4,' ',hcb:5:4,' ',hft:5:4,' ',hct:5:4,' ',
     xlt:5:4,' ',xrt:5:4,' ',xrb:5:4,' ',xlb:5:4,' ',ylt:5:4,' ',yrt:5:4,' ',yrb:5:4,' ',ylb:5:4,' ',
     zlt:5:4,' ',zrt:5:4,' ',zrb:5:4,' ',zlb:5:4,' ');}
end;

procedure loop;
begin
     writeln('Position focus lever       (min: - 8  max:  5.6)');
     writeln('Position convergence lever (min: -11  max: 17)');
     writeln;
     write('focus       ?'); readln(hf); hf:=hf*pi/180+pi;
     write('convergence ?'); readln(hc); hc:=hc*pi/180;

     while hf < 3.25 do
     begin
          write('hf ',hf:8:6);
          focus;
          dxf:=-x1; dyf:=-y1;
          convergence;
          store;
          hf:=hf + 0.01
     end;
end;
```

```
procedure input;
begin
    writeln;
    write('focus       ?'); readln(hf); hf:=hf*pi/180+pi;
    write('convergence ?'); readln(hc); hc:=hc*pi/180;
    focus;
    dxf:=-x1; dyf:=-y1;
    convergence;
end;

procedure inputlcd;
begin
    writeln('Position focus lever       (min: - 8  max:  5.6)');
    writeln('Position convergence lever (min: -11  max: 17)');
    writeln;
    write('focus side         ?'); readln(hfs); hfs:=hfs*pi/180+pi;
    write('convergence side   ?'); readln(hcs); hcs:=hcs*pi/180;
    write('focus bottom       ?'); readln(hfb); hfb:=hfb*pi/180+pi;
    write('convergence bottom ?'); readln(hcb); hcb:=hcb*pi/180;
    write('focus top          ?'); readln(hft); hft:=hft*pi/180+pi;
    write('convergence top    ?'); readln(hct); hct:=hct*pi/180;
end;

procedure draw_numbers;
var cxlt, fxlt, cylt, fylt, fzlt: real;
var cxrt, fxrt, cyrt, fyrt, fzrt: real;
var cxrb, fxrb, cyrb, fyrb, fzrb: real;
var cxlb, fxlb, cylb, fylb, fzlb: real;
begin

    cxlt:=sdxlt+bdxlt+tdxlt; fxlt:=sfxlt+bfxlt+tfxlt;
    cylt:=sdylt+bdylt+tdylt; fylt:=sfylt+bfylt+tfylt;
    fzlt:=sfzlt+bfzlt+tfzlt;
    cxrt:=sdxrt+bdxrt+tdxrt; fxrt:=sfxrt+bfxrt+tfxrt;
    cyrt:=sdyrt+bdyrt+tdyrt; fyrt:=sfyrt+bfyrt+tfyrt;
    fzrt:=sfzrt+bfzrt+tfzrt;
    cxrb:=sdxrb+bdxrb+tdxrb; fxrb:=sfxrb+bfxrb+tfxrb;
    cyrb:=sdyrb+bdyrb+tdyrb; fyrb:=sfyrb+bfyrb+tfyrb;
    fzrb:=sfzrb+bfzrb+tfzrb;
    cxlb:=sdxlb+bdxlb+tdxlb; fxlb:=sfxlb+bfxlb+tfxlb;
    cylb:=sdylb+bdylb+tdylb; fylb:=sfylb+bfylb+tfylb;
    fzlb:=sfzlb+bfzlb+tfzlb;

    writeln;
    writeln;
    write('cx ',cxlt:5:4,'=',sdxlt:5:4,'+',bdxlt:5:4,'+',tdxlt:5:4);
    writeln('      cx ',cxrt:5:4,'=',sdxrt:5:4,'+',bdxrt:5:4,'+',tdxrt:5:4);
    write('fx ',fxlt:5:4,'=',sfxlt:5:4,'+',bfxlt:5:4,'+',tfxlt:5:4);
    writeln('      fx ',fxrt:5:4,'=',sfxrt:5:4,'+',bfxrt:5:4,'+',tfxrt:5:4);
    write('   ',cxlt+fxlt:5:4); writeln('                              ',cxrt+fxrt:5:4);
    write('cy ',cylt:5:4,'=',sdylt:5:4,'+',bdylt:5:4,'+',tdylt:5:4);
    writeln('      cy ',cyrt:5:4,'=',sdyrt:5:4,'+',bdyrt:5:4,'+',tdyrt:5:4);
    write('fy ',fylt:5:4,'=',sfylt:5:4,'+',bfylt:5:4,'+',tfylt:5:4);
    writeln('      fy ',fyrt:5:4,'=',sfyrt:5:4,'+',bfyrt:5:4,'+',tfyrt:5:4);
    write('   ',cylt+fylt:5:4); writeln('                              ',cyrt+fyrt:5:4);
    write('fz ',fzlt:5:4,'=',sfzlt:5:4,'+',bfzlt:5:4,'+',tfzlt:5:4);
    writeln('      fz ',fzrt:5:4,'=',sfzrt:5:4,'+',bfzrt:5:4,'+',tfzrt:5:4);
    writeln;writeln;writeln;writeln;writeln;
```

```
     write('cx ',cxlb:5:4,'=',sdxlb:5:4,'+',bdxlb:5:4,'+',tdxlb:5:4);
     writeln('     cx ',cxrb:5:4,'=',sdxrb:5:4,'+',bdxrb:5:4,'+',tdxrb:5:4);
     write('fx ',fxlb:5:4,'=',sfxlb:5:4,'+',bfxlb:5:4,'+',tfxlb:5:4);
     writeln('     fx ',fxrb:5:4,'=',sfxrb:5:4,'+',bfxrb:5:4,'+',tfxrb:5:4);
     write('   ',cxlb+fxlb:5:4); writeln('                              ',cxrb+fxrb:5:4);
     write('cy ',cylb:5:4,'=',sdylb:5:4,'+',bdylb:5:4,'+',tdylb:5:4);
     writeln('     cy ',cyrb:5:4,'=',sdyrb:5:4,'+',bdyrb:5:4,'+',tdyrb:5:4);
     write('fy ',fylb:5:4,'=',sfylb:5:4,'+',bfylb:5:4,'+',tfylb:5:4);
     writeln('     fy ',fyrb:5:4,'=',sfyrb:5:4,'+',bfyrb:5:4,'+',tfyrb:5:4);
     write('   ',cylb+fylb:5:4); writeln('                              ',cyrb+fyrb:5:4);
     write('fz ',fzlb:5:4,'=',sfzlb:5:4,'+',bfzlb:5:4,'+',tfzlb:5:4);
     writeln('     fz ',fzrb:5:4,'=',sfzrb:5:4,'+',bfzrb:5:4,'+',tfzrb:5:4);

     write('press c to continue ');
     readln(ch);
     repeat until ch = 'c';
end;

procedure draw;
var m,k: real;
begin
     Driver:=detect;
     Initgraph(driver, modus, 'c:\talen\tp\bgi');

     setcolor(green);
     line(60, 60, 540, 60);
     moveto(540, 60);
     lineto(540, 390);
     lineto(60, 390);
     lineto(60, 60);

     m:=60; k:=10;

     setcolor(magenta);
     line(round(m+k*xlt), round(m-k*ylt), round(600-m+k*xrt), round(m-k*yrt));
     moveto(round(600-m+k*xrt), round(m-k*yrt));
     lineto(round(600-m+k*xrb), round(450-m-k*yrb));
     lineto(round(m+k*xlb), round(450-m-k*ylb));
     lineto(round(m+k*xlt), round(m-k*ylt));


     write('press c to continue ');
     readln(ch);
     repeat until ch = 'c';
     closegraph;
end;

procedure numbers;
var cxlt, fxlt, cylt, fylt, fzlt: real;
var cxrt, fxrt, cyrt, fyrt, fzrt: real;
var cxrb, fxrb, cyrb, fyrb, fzrb: real;
var cxlb, fxlb, cylb, fylb, fzlb: real;
begin

     cxlt:=sdxlt+bdxlt+tdxlt; fxlt:=sfxlt+bfxlt+tfxlt;
     cylt:=sdylt+bdylt+tdylt; fylt:=sfylt+bfylt+tfylt;
     fzlt:=sfzlt+bfzlt+tfzlt;
     cxrt:=sdxrt+bdxrt+tdxrt; fxrt:=sfxrt+bfxrt+tfxrt;
```

```
     cyrt:=sdyrt+bdyrt+tdyrt; fyrt:=sfyrt+bfyrt+tfyrt;
     fzrt:=sfzrt+bfzrt+tfzrt;
     cxrb:=sdxrb+bdxrb+tdxrb; fxrb:=sfxrb+bfxrb+tfxrb;
     cyrb:=sdyrb+bdyrb+tdyrb; fyrb:=sfyrb+bfyrb+tfyrb;
     fzrb:=sfzrb+bfzrb+tfzrb;
     cxlb:=sdxlb+bdxlb+tdxlb; fxlb:=sfxlb+bfxlb+tfxlb;
     cylb:=sdylb+bdylb+tdylb; fylb:=sfylb+bfylb+tfylb;
     fzlb:=sfzlb+bfzlb+tfzlb;


     writeln('left top');
     writeln('cx ',cxlt:16:14,'=',sdxlt:16:14,'+',bdxlt:16:14,'+',tdxlt:16:14);
     writeln('fx ',fxlt:16:14,'=',sfxlt:16:14,'+',bfxlt:16:14,'+',tfxlt:16:14);
     writeln('cy ',cylt:16:14,'=',sdylt:16:14,'+',bdylt:16:14,'+',tdylt:16:14);
     writeln('fy ',fylt:16:14,'=',sfylt:16:14,'+',bfylt:16:14,'+',tfylt:16:14);
     writeln('fz ',fzlt:16:14,'=',sfzlt:16:14,'+',bfzlt:16:14,'+',tfzlt:16:14);

     writeln('right top');
     writeln('cx ',cxrt:16:14,'=',sdxrt:16:14,'+',bdxrt:16:14,'+',tdxrt:16:14);
     writeln('fx ',fxrt:16:14,'=',sfxrt:16:14,'+',bfxrt:16:14,'+',tfxrt:16:14);
     writeln('cy ',cyrt:16:14,'=',sdyrt:16:14,'+',bdyrt:16:14,'+',tdyrt:16:14);
     writeln('fy ',fyrt:16:14,'=',sfyrt:16:14,'+',bfyrt:16:14,'+',tfyrt:16:14);
     writeln('fz ',fzrt:16:14,'=',sfzrt:16:14,'+',bfzrt:16:14,'+',tfzrt:16:14);

     writeln('right bottom');
     writeln('cx ',cxrb:16:14,'=',sdxrb:16:14,'+',bdxrb:16:14,'+',tdxrb:16:14);
     writeln('fx ',fxrb:16:14,'=',sfxrb:16:14,'+',bfxrb:16:14,'+',tfxrb:16:14);
     writeln('cy ',cyrb:16:14,'=',sdyrb:16:14,'+',bdyrb:16:14,'+',tdyrb:16:14);
     writeln('fy ',fyrb:16:14,'=',sfyrb:16:14,'+',bfyrb:16:14,'+',tfyrb:16:14);
     writeln('fz ',fzrb:16:14,'=',sfzrb:16:14,'+',bfzrb:16:14,'+',tfzrb:16:14);

     writeln('left bottom');
     writeln('cx ',cxlb:16:14,'=',sdxlb:16:14,'+',bdxlb:16:14,'+',tdxlb:16:14);
     writeln('fx ',fxlb:16:14,'=',sfxlb:16:14,'+',bfxlb:16:14,'+',tfxlb:16:14);
     writeln('cy ',cylb:16:14,'=',sdylb:16:14,'+',bdylb:16:14,'+',tdylb:16:14);
     writeln('fy ',fylb:16:14,'=',sfylb:16:14,'+',bfylb:16:14,'+',tfylb:16:14);
     writeln('fz ',fzlb:16:14,'=',sfzlb:16:14,'+',bfzlb:16:14,'+',tfzlb:16:14);

     write('press c to continue ');
     readln(ch);
     repeat until ch = 'c';
end;

procedure length;
function l(x,y: real): real;
begin
     if x>y then l:=x-y else l:=y-x;
end;

begin
     write(sqrt(sqr(l(xlt,xrt)+2*w)+sqr(l(ylt,yrt))+sqr(l(zlt,zrt))));
     write(2*w);
     writeln(sqrt(sqr(l(xlt,xrt)+2*w)+sqr(l(ylt,yrt))+sqr(l(zlt,zrt)))-2*w);

     write(sqrt(sqr(l(xlb,xrb)+2*w)+sqr(l(ylb,yrb))+sqr(l(zlb,zrb))));
     write(2*w);
     writeln(sqrt(sqr(l(xlb,xrb)+2*w)+sqr(l(ylb,yrb))+sqr(l(zlb,zrb)))-2*w);
```

```
     write(sqrt(sqr(l(xlt,xlb))+sqr(l(ylt,ylb)+2*h)+sqr(l(zlt,zlb))));
     write(2*h);
     writeln(sqrt(sqr(l(xlt,xlb))+sqr(l(ylt,ylb)+2*h)+sqr(l(zlt,zlb)))-2*h);

     write(sqrt(sqr(l(xrt,xrb))+sqr(l(yrt,yrb)+2*h)+sqr(l(zrt,zrb))));
     write(2*h);
     writeln(sqrt(sqr(l(xrt,xrb))+sqr(l(yrt,yrb)+2*h)+sqr(l(zrt,zrb)))-2*h);

     write(sqrt(sqr(l(xlt,xrb)+2*w)+sqr(l(ylt,yrb)+2*h)+sqr(l(zlt,zrb))));
     write(sqrt(sqr(2*h)+sqr(2*w)));
     writeln(sqrt(sqr(l(xlt,xrb)+2*w)+sqr(l(ylt,yrb)+2*h)+sqr(l(zlt,zrb)))-sqrt(sqr(2*h)+sqr(2*w)));

     write(sqrt(sqr(l(xrt,xlb)+2*w)+sqr(l(yrt,ylb)+2*h)+sqr(l(zrt,zlb))));
     write(sqrt(sqr(2*h)+sqr(2*w)));
     writeln(sqrt(sqr(l(xrt,xlb)+2*w)+sqr(l(yrt,ylb)+2*h)+sqr(l(zrt,zlb)))-sqrt(sqr(2*h)+sqr(2*w)));

     write('press c to continue ');
     readln(ch);
     repeat until ch = 'c';
end;


procedure all;
var a,b,c,d,e,f,g: integer;
begin
a:=0;b:=0;c:=0;d:=0;e:=0;f:=0;g:=0;
     for a:=1 to 3 do
     begin
          if a=1 then hfs:=-8*pi/180+pi;
          if a=2 then hfs:=0*pi/180+pi;
          if a=3 then hfs:=5.6*pi/180+pi;
          for b:=1 to 3 do
          begin
               if b=1 then hcs:=-11*pi/180;
               if b=2 then hcs:=0*pi/180;
               if b=3 then hcs:=17*pi/180;
               for c:=1 to 3 do
               begin
                    if c=1 then hfb:=-8*pi/180+pi;
                    if c=2 then hfb:=0*pi/180+pi;
                    if c=3 then hfb:=5.6*pi/180+pi;
                    for d:=1 to 3 do
                    begin
                         if d=1 then hcb:=-11*pi/180;
                         if d=2 then hcb:=0*pi/180;
                         if d=3 then hcb:=17*pi/180;
                         for e:=1 to 3 do
                         begin
                              if e=1 then hft:=-8*pi/180+pi;
                              if e=2 then hft:=0*pi/180+pi;
                              if e=3 then hft:=5.6*pi/180+pi;
                              for f:=1 to 3 do
                              begin
                                   if f=1 then hct:=-11*pi/180;
                                   if f=2 then hct:=0*pi/180;
                                   if f=3 then hct:=17*pi/180;
                                   redlcd;
                                   store;
```

```
                                    g:=g+1;
                                    writeln(hfs:5:4,'  ',hcs:3:2,'  ',hfb:3:2,'  ',hcb:3:2,'  ',hft:3:2,'
                                                                ',hct:3:2,' ',g);
                                    xlt:3:2,' ',xrt:3:2,' ',xrb:3:2,' ',xlb:3:2,' ',
                                    ylt:3:2,' ',yrt:3:2,' ',yrb:3:2,' ',ylb:3:2,' ',
                                    zlt:3:2,' ',zrt:3:2,' ',zrb:3:2,' ',zlb:3:2,' ');

                                end;
                            end;
                        end;
                    end;
                end;
            end;
        end;



begin
    write('input filename ');
    readln(filename);
    assign(edge,filename);
    rewrite(edge);
    all
    loop;
    store;
    close(edge);
    inputlcd;
    redlcd;
    draw;
    draw_numbers;
    numbers;
    length;
end.
```

RED								
nr	left	top	right	top	right	bottom	left	bottom
	X	Y	X	Y	X	Y	X	Y
243	0	-3	-1	-2	0	-1	0	-2
244	-1	-2	-1	0	1	0	1	-3
245	4	-1	5	-2	3	-3	3	0
246	-1	0	-1	2	1	2	0	2
247	4	-5	5	-7	3	-7	2	-5
248	-1	-5	-1	-5	-1	-4	-2	-4
249	3	-5	3	-4	4	-4	5	-5
250	-4	0	-3	2	-3	2	-2	0
255	-1	0	-2	4	1	5	1	0
256	0	-3	0	-2	0	-2	0	-2
257	4	0	4	3	5	1	5	4
258	1	0	1	4	4	4	4	0
259	1	3	0	5	1	6	2	5
260	2	-5	2	-6	2	-4	3	-4
261	2	-1	2	0	2	0	2	-1
262	0	-4	0	0	2	-1	3	-3
avg	0.72	-1.72	0.72	-0.44	1.39	-0.33	1.50	-1.00
sd	2.08	2.30	2.26	3.40	1.92	3.30	2.03	2.75
BLUE								
nr	left	top	right	top	right	bottom	left	bottom
	X	Y	X	Y	X	Y	X	Y
243	-3	-5	-4	-4	-2	-3	-2	-6
244	-3	-2	-3	-3	-4	-3	-4	-3
245	0	-3	0	-2	-2	-5	-2	-2
246	-2	0	-3	-3	-4	-3	-4	1
247	1	-5	1	-4	1	-4	1	-5
248	-5	-3	-6	1	-5	2	-5	-1
249	0	0	1	1	2	2	3	0
250	-7	0	-6	2	-5	3	-4	0
255	2	4	2	7	3	8	3	6
256	0	-3	0	0	2	0	2	-2
257	-1	3	-1	0	-4	0	-3	4
258	0	3	0	3	0	4	0	4
259	3	2	2	3	2	4	3	3
260	0	1	0	2	0	3	1	2
261	0	0	0	0	0	1	0	-1
262	-4	-4	-4	-3	-4	-3	-3	-4
avg	-0.65	-0.75	-0.73	0.13	-0.58	0.36	-0.25	-0.28
sd	2.40	2.60	2.44	2.62	2.61	3.08	2.61	2.98

nr	conv blue top	focus blue top	conv blue side	focus blue side	conv blue bottom	focus blue bottom	conv red top	focus red top	conv red side	focus red side	conv red bottom	focus red bottom
97	0	1	1	1	1	0	-2	0	1	3	0	-1
111	1	1	1	0	-1	2	-1	-1	3	-1	-2	0
188	1	2	-1	1	-2	0	-1	0	0	1	1	-2
201	2	1	0	2	2	2	1	1	-1	0	-1	1
202	-3	1	1	1	-2	2	0	-1	2	-1	1	-1
203	-1	1	1	2	1	1	1	-1	1	-1	0	0
204	2	2	-2	2	0	1	0	-1	-1	0	1	-1
205	0	0	-1	0	-1	1	-3	-1	-1	2	-2	-2
206	2	2	1	2	-1	2	0	-1	-1	2	-1	-1
208	-1	1	1	2	-2	-2	-1	0	3	-2	-2	3
210	1	2	0	2	0	2	-1	-1	1	0	1	0
211	1	1	1	0	1	2	-2	-1	2	-1	-1	1
212	2	2	0	2	1	2	0	2	-1	2	1	-1
213	0	2	-2	2	2	2	1	-1	3	-1	3	1
214	-1	0	0	2	-3	2	1	-2	-2	0	-1	-1
215	-1	1	0	2	-1	2	0	0	0	0	0	-1
216	-1	1	-1	2	-1	-2	0	2	0	2	0	-1
217	0	2	-1	2	-1	2	-2	2	0	0	-1	-2
223	0	0	-1	2	2	2	-2	-1	1	0	1	3
224	-1	0	-1	2	-1	0	0	-1	1	1	-1	1
225	2	0	0	2	0	2	-1	0	-2	2	-2	-1
226	1	1	2	3	-1	2	0	0	-2	0	-2	0
227	1	0	0	0	1	0	0	0	-1	0	0	0
228	1	1	2	2			-1	1	0	2		
229	0	1	2	2	-1	2	0	-2	0	-2	-2	2
230	1	-1	1	0	-1	2	-2	0	-2	0	-2	-1
231	1	2	0	0	2	0	1	-1	0	-1	0	0
232	2	2	-1	3	2	2	-2	-1	-2	2	-1	0
233	1	0	0	0	0	0	0	0	-1	-1	0	-1
235	2	0	1	0	1	-1	-1	1	-2	-1	1	-1
238	1	1	2	0	-1	2	-1	-1	-1	2	-1	0
239	2	2	0	0	1	0	-1	0	0	0	1	0
240	3	0	3	2	2	2	0	-1	0	-1	2	0
245	-1	1	0	-1	0	-2	-2	-1	1	1	-2	2
247	0	0	3	2	1	3	0	-1	1	-1	-2	-2
248	1	2	-1	2	3	2	1	-1	3	-1	0	2
249	3	2	3	3	2	2	2	-1	3	-1	1	0
250	0	1	0	2	0	3	1	2	-1	-1	0	0
251	1	2	-1	2	-2	-1	-2	-3	2	-1	0	0
252	1	2	0	2	2	2	-1	0	-2	0	-1	0
253	-1	2	0	2	0	3	2	-2	3	-1	-2	-1
254	1	2	-1	2	3	2	0	-1	1	0	2	2
255	2	3	1	2	0	2	-2	0	0	-1	-1	0
256	-1	3	0	2	0	2	0	0	1	0	0	0
57	-1	0	-1	1	-1	1	1	-2	0	-1	-1	-1
58	0	-1	-2	1	1	-2	-2	-1	1	3	0	1
60	1	1	-1	2	1	2	-2	2	-1	0	0	-1
	0.57	1.11	0.19	1.47	0.20	1.20	-0.49	-0.40	0.21	0.09	-0.33	-0.09
	1.25	0.95	1.27	0.96	1.44	1.38	1.20	1.14	1.54	1.29	1.25	1.23