Capstan Drive Transport System for Motion Picture Film

thesis submitted to the Council for National Academic Awards in partial fulfilment of the requirements for the degree of Doctor of Philosophy

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To my wife, Jenny.

If I have seen further it is by

standing on the shoulder of giants.

SIR ISAAC NEWTON 1675

Abstract

The work presented describes the development of a capstan drive system for the transport of motion picture film. From a model description of the plant and computer aided system design analysis, control algorithms are formulated. The work shows how these relativity complex control algorithms are implemented by making use of the parallel processing capabilities of the transputer.

A critical investigation of current film transport methods is undertaken leading to the design and testing of a prototype capstan drive mechanism. The capstan drive system is shown to eliminate problems of sprocket drives and their associated mechanisms.

A multi-input multi-output controller is presented using state-space methods of design. The developed control strategies are fully tested on a model of the plant before hardware testing. The control outputs of the system are speed and tension. The final control solution is shown to be a combination of full-state feedback, integral control, and a Kalman filter estimator for the elimination of system disturbances.

The transputer implementation of the developed control strategies is presented together with a comparison between simulation and experimental results. It is shown that computational times can be reduced by using multiple transputers and placing computation-intensive sections of the control algorithm on separate processors. Transputer configurations and interconnections are shown.

The capstan system has been shown to allow faster printing speeds with improved transport accuracy leading to better quality of the final picture print. The system has been shown to be 'robust' to external disturbances and changes in plant parameters.

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Glossary of Terms

ACSL - Advanced continuous simulation language.

ADC - Analog-to-digital converter.

CASD - Computer aided system design.

CPU - Central processing unit.

DAC - Digital-to-analog converter.

DC - Direct current.

FPU - Floating point unit.

I/O - Input output.

LQR - Linear quadratic regulator.

MIMO - Multi-input multi-output.

MIPS - Million instructions per second.

MISO - Multi-input single-output.

RAM - Random access memory.

ROM - Read-only memory.

SISO - Single-input single-output.

ZOH - Sero order hold.

List of Symbols

A,**B**,**H** - continous system descriptor matrices.

C - film damping coefficient

i - current

I - unity matrix

J - quadratic cost function

J - Inertia

k - sample counter

K - film stifness

K - gain matrix

$K_1, K_2,..$ - gain elements

K_d - damping constant

K_t - torque constant

L - Kalman filter gain matrix

M - expected mean square error

$\mathbf{N}_x$ - state command matrix

n - number of states

o - number of outputs

$\mathbf{Q}_{1,2}$ - cost function weightings

r - number of controls

r - reference input

s - eigenvalues

$\mathbf{S}_{ss}$ - steady state solution of Riccati equation

T - film tension

u - input state matrix

V - film speed

w - process noise

v - measurement noise

x - state matrix

$x_1, x_2,..$ - state elements

$\mathbf{x}_r$ - reference state

$\bar{\mathbf{x}}$ - predicted state estimate

$\hat{\mathbf{x}}$ - current state estimate

$\mathbf{y}$ - output state matrix

$\mathbf{\Phi}$, Γ - discrete system descriptor matrices

τ_f - torque friction

ω, Ω- angular velocity

ζ - damping ratio

Chapter 1

Introduction

The production route of motion picture film from the film studio to the cinema involves many intermediate processes. The final product is always the same - an image. The "image technology" associated with each of these intermediate processes includes chemical control (developer), image colour analysis (grading), special effects, and other production control techniques all of which contribute to the quality of the final image.

Some of the technology involved is very sophisticated and employs modern manufacturing techniques. Some processes have changed very little and still remain time consuming and labour intensive. A typical film processing laboratory can produce up to 0.3 million metres of film in one week, this may include many different films. The only satisfactory way to inspect the print before it is dispatched is manually, usually on high speed viewers. This has to be done for every metre of film.

The work covered in this study is concerned primarily with the copying of film and in particular the bulk copying process which is usually carried out on high speed panel printing machines. Film copying is a critical part of the production of motion picture film. If the master copy produced from the original contains picture unsteadiness this is reflected through all the subsequent processes.

Film transport drive mechanisms associated with these panel printers consist of sprockets to drive the film and have mechanical gears to drive the sprockets. Use of these mechanical drives and their associated control systems has limited the printing speed of film to typically 2.5-3.0 m/s (500-800 ft/min).

New requirements for motion picture release printing and the development of new technologies has prompted the development of new printer and printing systems. Despite this, the only successful high-speed printing system (5m/s) is one developed by Technicolor, Inc. [Michelson, 1976], which utilises a microprocessor to control the printing system. This system still has the draw back of employing sprocket drive and is only capable of printing in one direction.

1.1 Film Processing Procedures.

Examination of printing methods raises a number of questions relating to the reasons for certain steps, the choice of materials and the preference of one method over another. Figure 1.1 shows a schematic of the general procedures used in the processing of motion picture film. This process has been broken down into several distinct steps [Collard, 1990].

- ☐ Film from the studio arrives in an un-processed form. It is unloaded manually from the canisters in complete darkness. The film is checked for any tears or broken perforations that might subsequently damage the film during processing. The film is then loaded onto the negative developer. This process has to be completed with great care because this is the original film.

- ☐ Once the film has been developed it is sent for cleaning, this takes place in special ultrasonic cleaners. The next stage is the production of the original negative print, this is performed on a contact printer. Details of the contact printer and its transport mechanism will be explained later. Contact printing is where the negative original and the raw stock are printed in contact with each other, emulsion to emulsion. It produces an image the same size as the original negative and the printed image is a mirror image of the original. The negatives (rushes) are stored in the laboratories vaults while the original print is send to the editor. The editor views the film and marks down the sections of the film to be included in the final copy.

- ☐ Once the final cutting copy has been returned to the laboratory it is the job of the negative cutter to fit together the final film from the original negative. Two film rolls are made during this negative cutting, 'A' and 'B' rolls. Successive scenes are cut alternatly into the 'A' negative roll and the 'B' negative roll, (see Appendix A). Opaque black leader is joined between scenes on each roll, to match exactly the length of the missing scenes.

- ☐ Before these negatives can be printed, cuing and grading operations must take place. Cuing involves marking the film to indicate to the printing machine a change of scene or a scene dissolve. Each scene on the film then has to be individually colour graded on a colour analyzer. It is important to colour grade each scene relative to the previous and subsequent scene. A record is made of the grading operations which is used by the printing machines to allow the appropriate printer light valves to be set, (red, green, blue).

- ☐ Before printing the cut negatives are again cleaned. A print is made in two passes on the contact printer, printing the 'A' and 'B' roll in succession onto the print stock. When the negatives are cut in 'A' and 'B' rolls, it is possible to incorporate fades and dissolves by overlapping scenes on the two rolls, and closing and opening a fader on the printing machine at the appropriate places, (see Appendix A).

- ☐ The result of this printing stage is a answer print or final trial print. This fully graded print is sent back to the editor for final approval. At this stage any re-grading adjustments can be made.

- ☐ At this stage we have one original cut negative. It is necessary to produce duplicate negatives for multiple release printing. This ensures that the original is protected against wear and tear from the sprockets on the printing machines.

- ☐ The duplication of films for multiple release is usually carried out on high speed contact printers known as panel printers. Panel printers are bi-directional and have printing speeds from 1.2 m/s (240 feet/min) to 5.0 m/s (1000 feet/min). This avoids the need to unlace the negatives after each pass. The negatives are cleaned by air knives during each pass on the printer.

Figure 1.2 shows the most widely used printing routes and material used by the film laboratory to make picture prints from original footage. Collard [1982, pp288] indicates that the choice of duplication route is influenced by several factors; choice of camera original stock, economic considerations, and quality considerations.

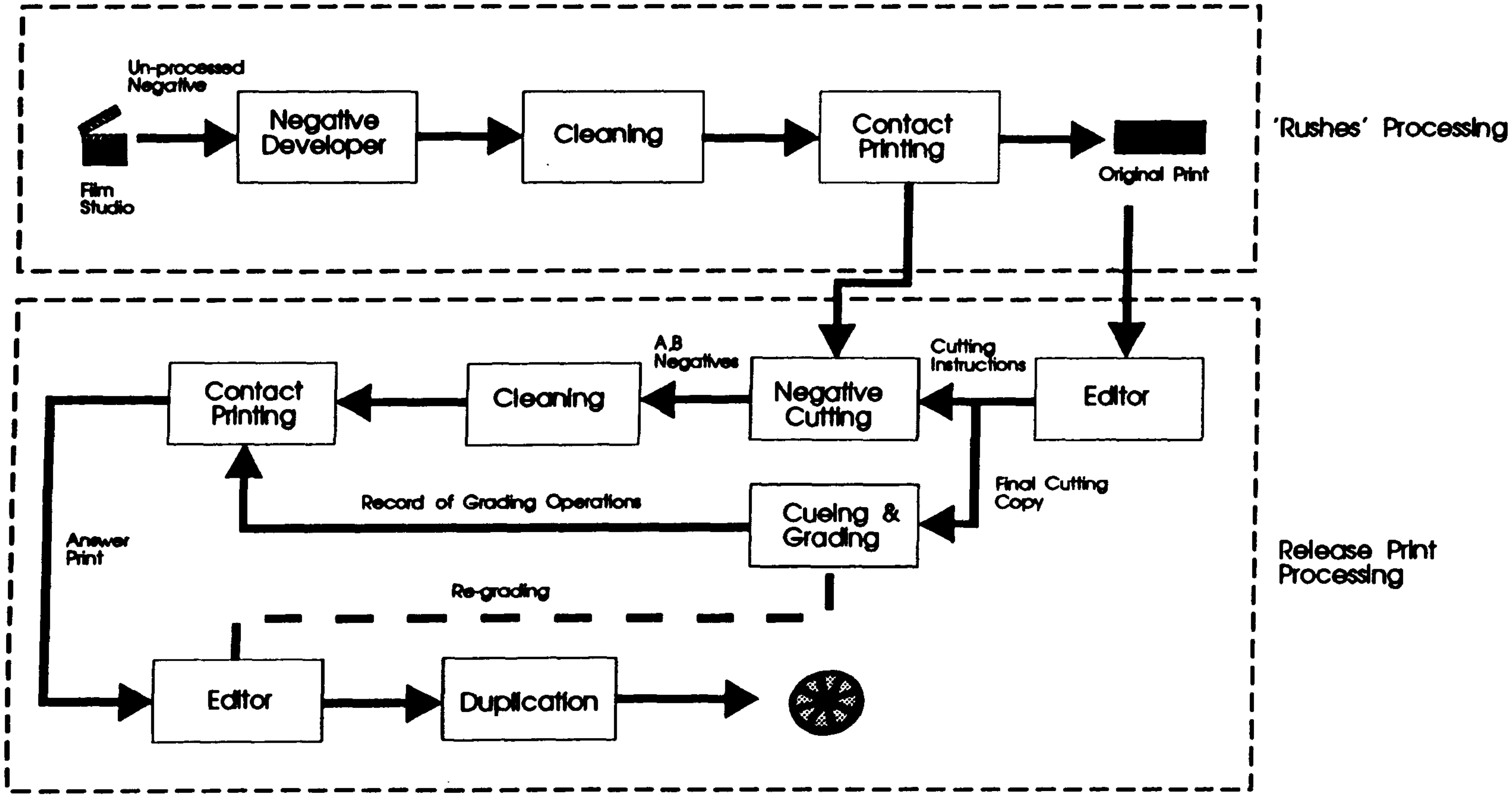

Figure 1. 1 - Outline of film processing procedures

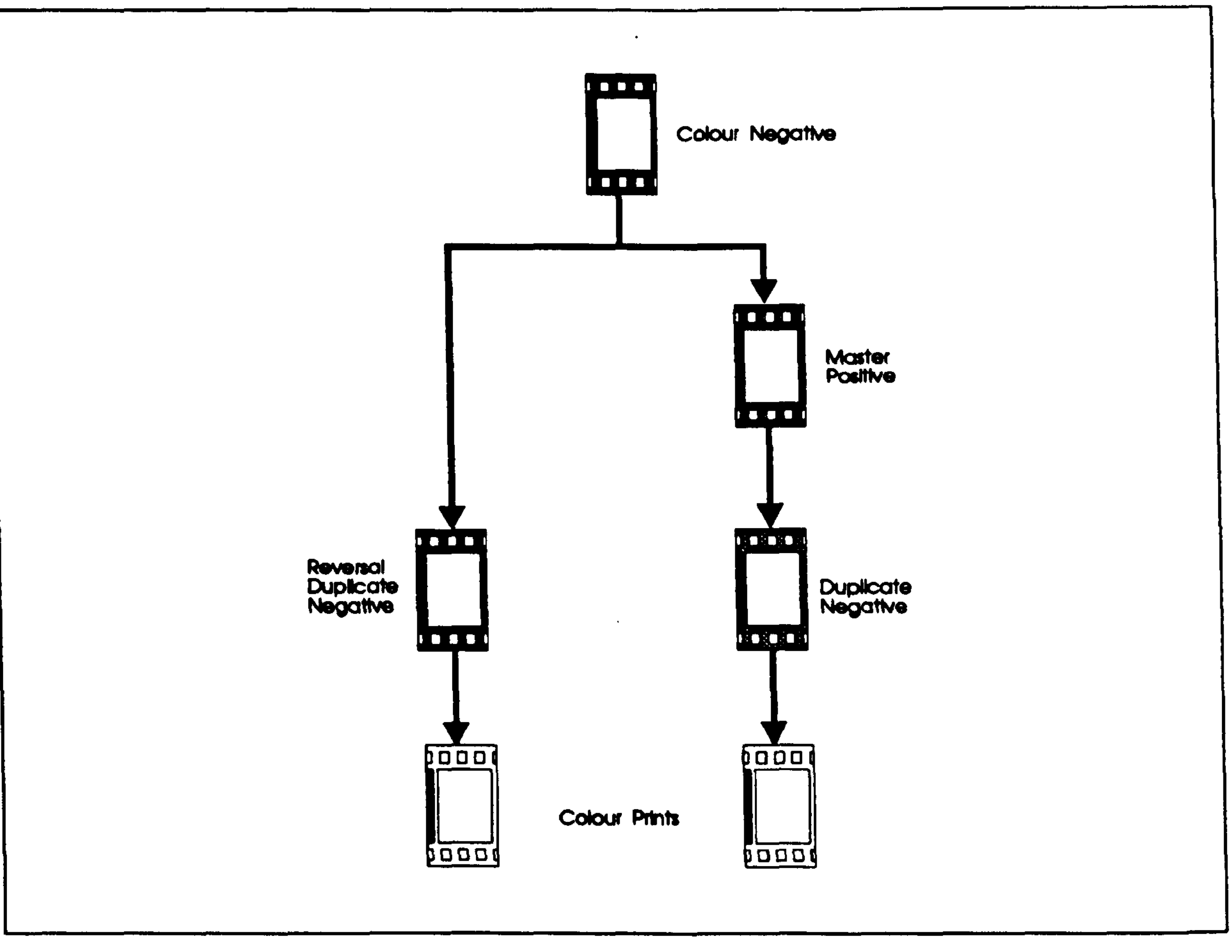

Figure 1.2 - Duplication routes

1.2 Basic Principles of Printing

1.2.1 Printing equipment

During the production of the final show print several types of specialised printing equipment can be used. Certain printing methods require a continuous or step-type contact printer with provision for scene density and colour-balance changes. To make reductions or enlargements, an optical printer is needed. If the method involves the use of separation positive for archival purposes, a registering type optical printer is used. Some kinds of special effects also require optical and/or registration printers. Printers having either subtractive or additive systems for controlling the colour and intensity of the printing illuminations can be used, but the additive system is the most widely used because of its greater versatility and precision.

Printing machines produce copies of films at high speed. This action of printing is accomplished by transporting the original film and the undeveloped film stock across a

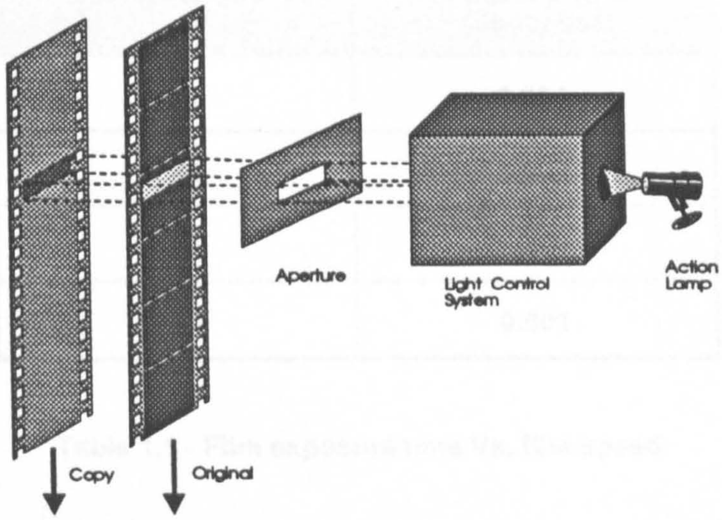

Figure 1.3 - Basic printing principles

slot or aperture at the same rate. A light is shone through the aperture, through the original film and onto the undeveloped stock, (see figure 1.3).

The exposure of the copy depends mainly on the following factors:

- Speed of the film as it is transported across the aperture,
- Size of the aperture (4.775 mm for 35 mm film),
- Intensity of the light source.

Printing machines contain two principal systems:

Light Control System - This delivers to the aperture a light of a precisely controlled intensity and colour balance. The light is produced by a halogen bulb of known intensity, this is known as the action lamp.

Film Transport System - This pulls the film through the machine. It also determines the speed and tension of the original film and the copy stock as they are both pulled across the printing aperture.

On Model 'C' printing machines which print original negatives the film is moved across the aperture at speeds between 0.9 and 1.0 m/s. On panel printers which use duplicate negatives for bulk copying, the speed of the film can be up to 4.57 m/s. Each part of the

Film Speed (ms^{-1})	Exposure Time (Seconds)
1.22	0.004
2.44	0.002
3.05	0.0015
4.57	0.001

Table 1.1 - Film exposure time Vs. film speed

film at 4.57 m/s therefore takes about 1 thousandth of a second to cross the aperture, (exposure time = 0.001 s), see table 1.1.

1.2.1.1 Action printing

In the last section figure 1.3 which illustrated a diagrammatic representation of the printing process it showed the original film and the raw stock travelling in the same direction, in a straight line and with a gap between them. In practice the raw stock and the original negative are in contact with each other as they cross the printing aperture. The aperture is in fact a slot cut into a circular printing head and the film travels over this head, (see figure 1.4).

The films are held in contact with the picture head by a roller. This roller gate is pulled down onto the film by a spring and rotates as the film passes under it. A stop screw is adjusted so that pressure exerted on the film is of a predetermined amount. Too much pressure will cause distortion of the film resulting in Newton's ring effects, too little pressure will cause the film to separate. The roller gate gap is usually set to 2 thicknesses of film less 0.0254 mm, using negative and un-processed film to achieve this gap, plate 1.1 shows how the roller gate can be lifted clear of the film to ease the lacing of the film stocks.

The steadying effect of this roller gate is further enhanced by film tension rollers on either side of the printing aperture.

Plate 1.1 - Picture head roller gate

35mm picture head

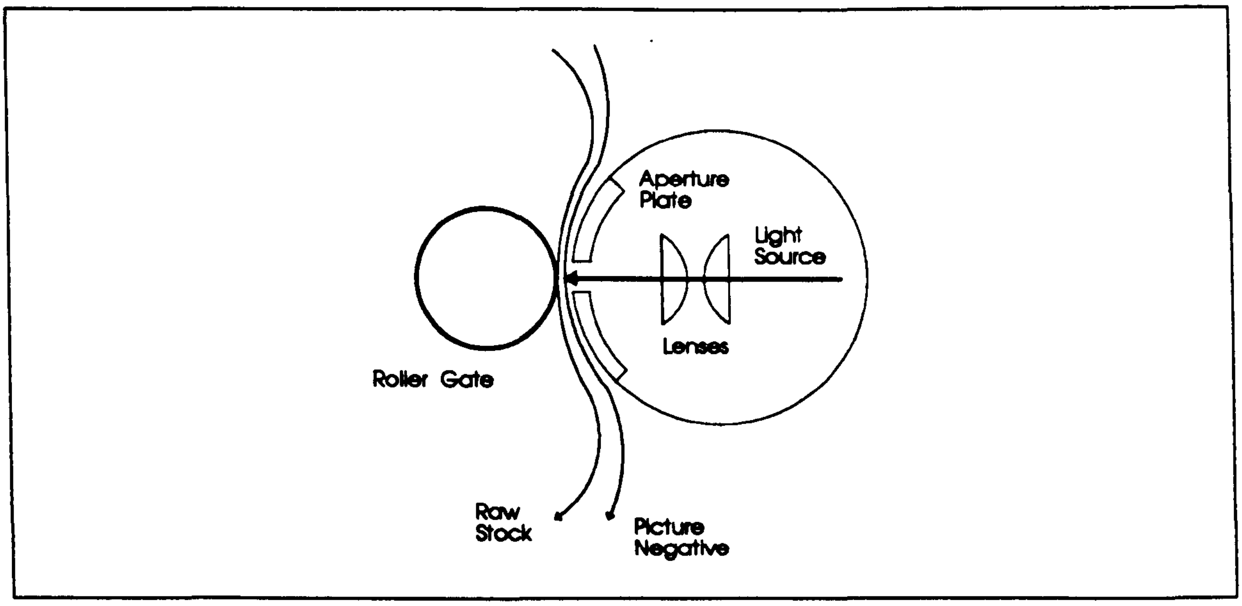

Figure 1.4 - Circular Printing Head + Film Lacing Path

1.2.2 Printing method quality considerations

The assessment of print quality involves considerations of a number of characteristics. As Collard points out [1982, pp.289] some are objective and other subjective, (choice of a method based on the amount of prints required). The quality of prints from the method chosen will depend on the film and the degree of care exercised in printing and processing. In evaluating quality, the following characteristics have been identified [Kodak, 1983] and will vary in importance depending on the use of the final print:

- Steadiness.
- Physical blemishes:- scratches, streaks, blotches, dirt particles, black and/or white specks.
- Graininess.
- Definition.
- Colour reproduction.
- Tone reproduction.
- Edge effects.

Quality is best judged by viewing prints under the projection conditions for which they are intended. Where the prints are to be used for normal projection before groups of people, the review room should simulate average viewing conditions with respect to projection distance, screen size, screen type, ambient light level and viewing distance.

1.2.3 Other considerations

Original footage has to be thoroughly cleaned and inspected for emulsion or base scratches. Typical frames are checked with a magnifier or microscope to ensure that the images are in sharp focus. A printing method cannot produce good definition if the original is not sharp.

Edited original footage is timed scene to scene for both density and colour to obtain the highest quality print. Even where original photography has been carried out in the most professional manner, scene to scene colour balance adjustment during printing is needed. This relates to the inability of the human eye to adapt quickly enough to scene changes causing the appearance of a scene to be influenced by the composition and colour attributes of the preceding scene.

Films used in the printing methods differ in graininess and modulation-transfer function. (The modulation-transfer function indicates the efficiency with which films reproduce details of the images that fell on them. Factors such as diffusion of light within the emulsion and adjacency effects in development influence the quality of reproduction). Optical systems have also specific modulation-transfer characteristics that can affect the graininess and sharpness observed in the final print.

One important criterion for choosing a printing method is the number of prints against which the cost can be offset. For example, reversal release prints made directly from the original might be the most economical approach when only a few prints are required, but not so when large quantities are involved.

It can be seen that the choice of a printing method is governed not only by the equipment and facilities available at the laboratory, but also by economical considerations, such as the cost of materials and labour for processing and printing, the number of prints desired, etc.

Improvements to the print process have described by Seys [1978, pp436]. He describes how these can be achieved through speeding up, as much as possible, the printing and processing operations. He also discusses the implications of high-speed printing. Seys in another paper as far back as 1960 [Seys et al, 1960] proposed that film processors, then operating at a maximum speed of 0.83 m/s for the development of colour print, must be modified to further increase the speed of the process.

The final print quality is dependent on a number of factors, including the quality of the original footage, the characteristic of the sensitised materials involved, the kind of equipment used and how well adjusted and maintained it is, the degree of control exercised in film processing, projection circumstances and the manner in which the film is handled.

1.3 Details of Printing Machines

The main study undertaken during this research has focused on the high speed bulk printing process and the associated printing machines, namely panel printers.

Panel printers are used for the bulk production of printed film using one negative over and over again. Panel printers are so designed to enable the printing process to be carried out in both directions over the printing heads. This enables the negative to be left on the machine until the number of copies required is reached or more commonly until the negative becomes worn. The panel printer, (see plate 1.2), consists of three main parts:

1.3.1 Picture head

Plate 1.3 shows the picture head for a 35 mm panel printer. The undeveloped positive stock passes over the picture head together with the picture negative, (see figure 1.5). The film is in contact with three sets of sprocket teeth, the two intermediate sprockets isolate the film in the printing head area from the rest of the machine, while the main sprocket drive acts as a registering point for the contact of the positive and negative film. Registration is achieved by means of a tension differential which is set up by using tensioning arms located, for each strand of film, on either side of the printing aperture. Figure 1.6 shows how this tension differential allows registration for both directions of printing. One factor that has been shown to cause problems in the printing process [Stoker, 1987] is the design of the main drive sprocket. As illustrated in figure 1.6 the main drive sprocket drives the film on one side. The reason for this type of configuration is the need for a direct light path onto the surface of the film.

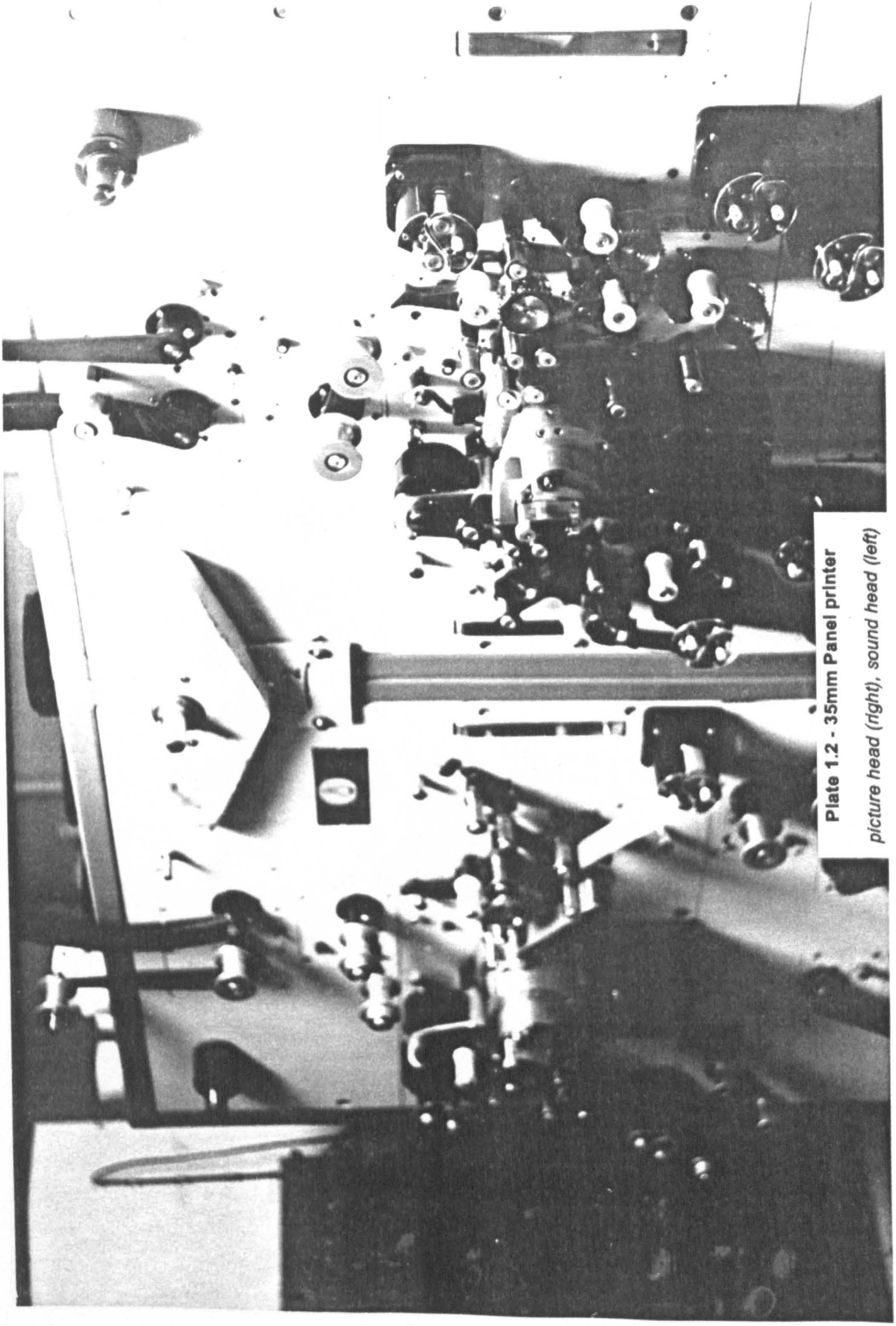

Plate 1.2 - 35mm Panel printer

picture head (right), sound head (left)

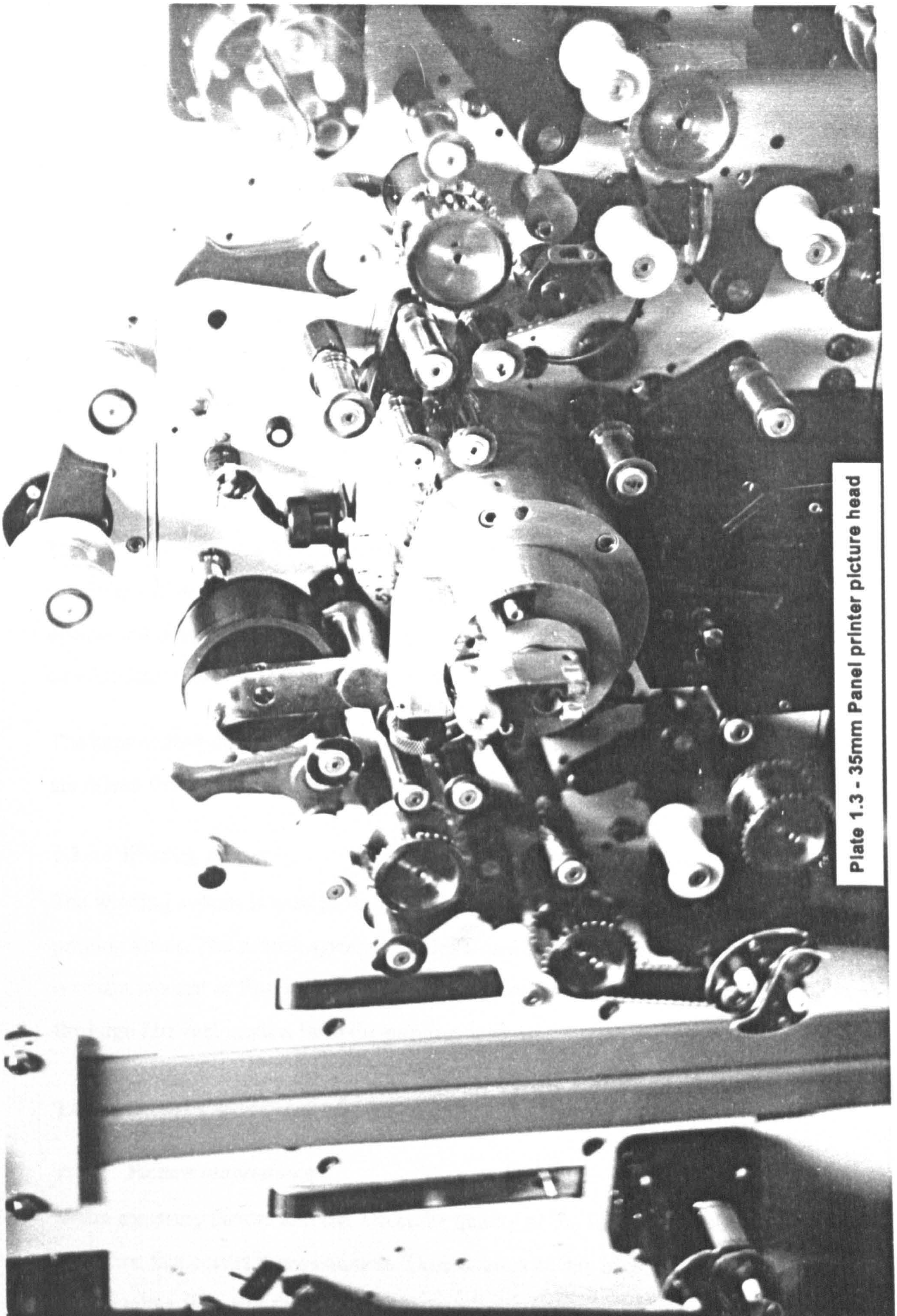

Plate 1.3 - 35mm Panel printer picture head

1.3.2 Sound head

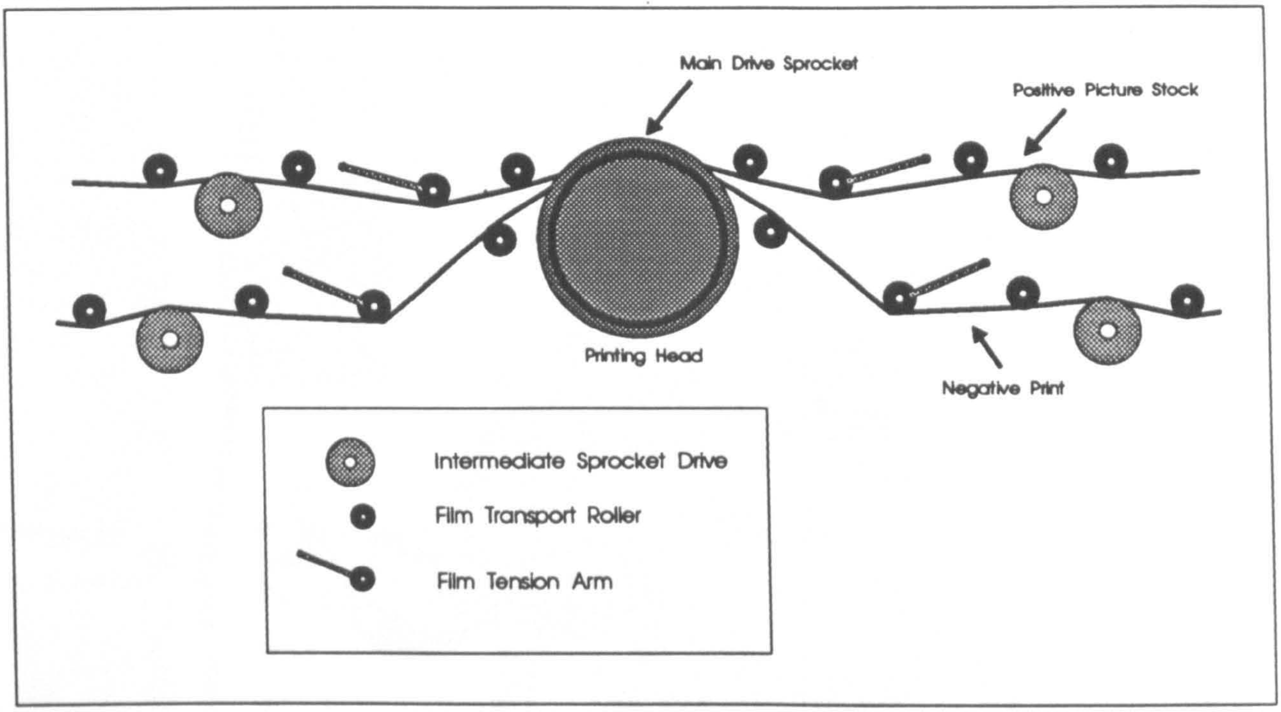

Figure 1.5 - Picture head lacing path

The layout of the sound head is identical to that of the picture head except that instead of picture negative, sound negative is passed over the head with the copy positive stock. The optical sound track runs along one edge of the film and is subject to the same printing considerations as those of the picture image.

The intermediate drive sprockets on either side of the printing head and the main sprocket are driven from a single motor. Gears connect the motor to the sprockets, Plate (1.4).

1.3.3 Winding system

The winding system is used to feed and take-up film to and from the picture and sound printing heads. The control system includes a dancer arm which is used to ensure that an constant amount of film is delivered to the printing heads and also buffers the effects of the large film reel inertias from the printing head drive system.

1.4 Problems Associated with Existing Printing Processes

1.4.1 Picture unsteadiness

There are many factors that can affect the quality of the final print and one of the major problems that occurs is unsteadiness. Unsteadiness occurs in most instances as a result of the negative film and the positive raw stock moving relative to each other during the

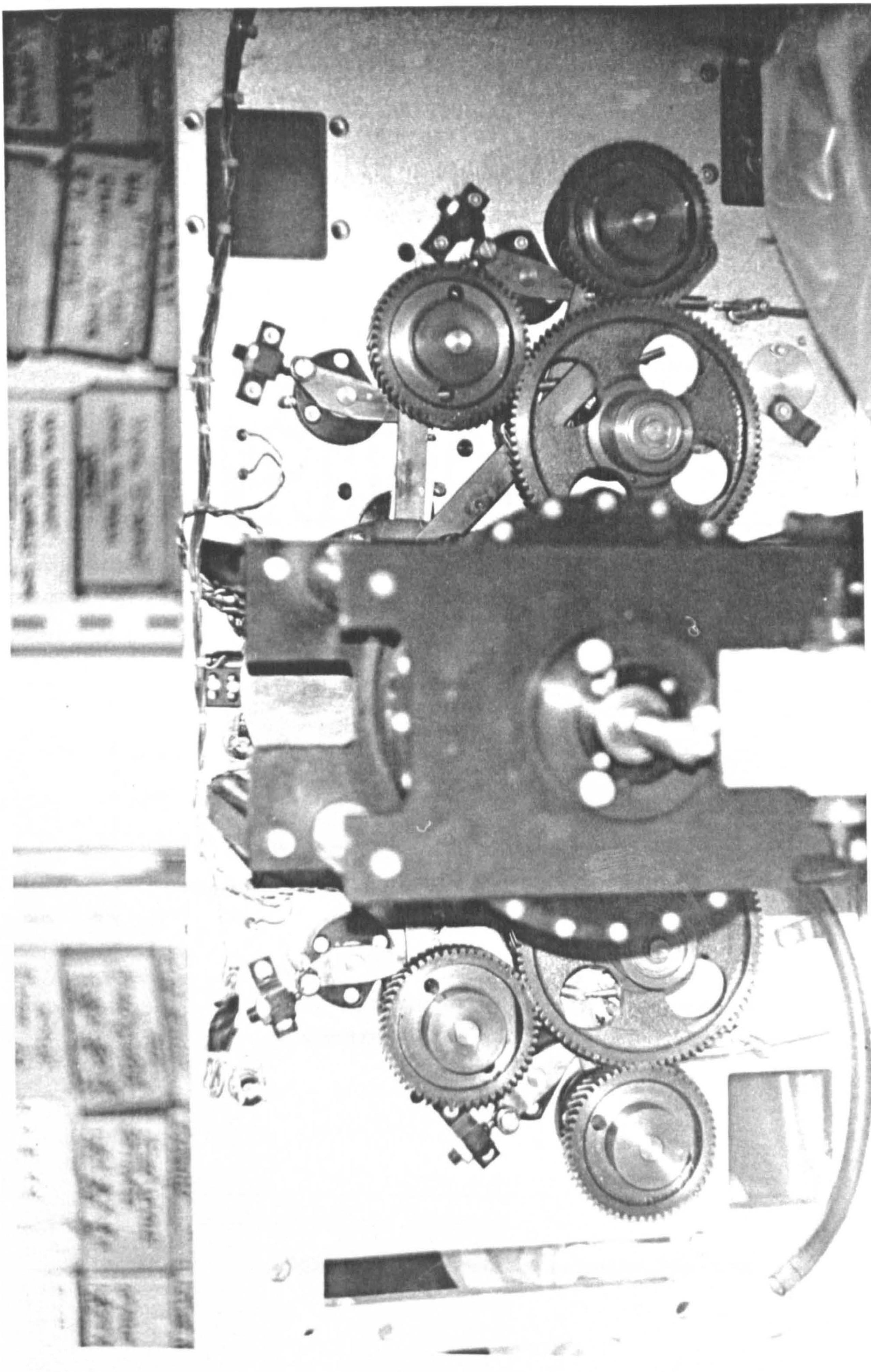

Plate 1.4 - Gear transmission for 35mm picture head

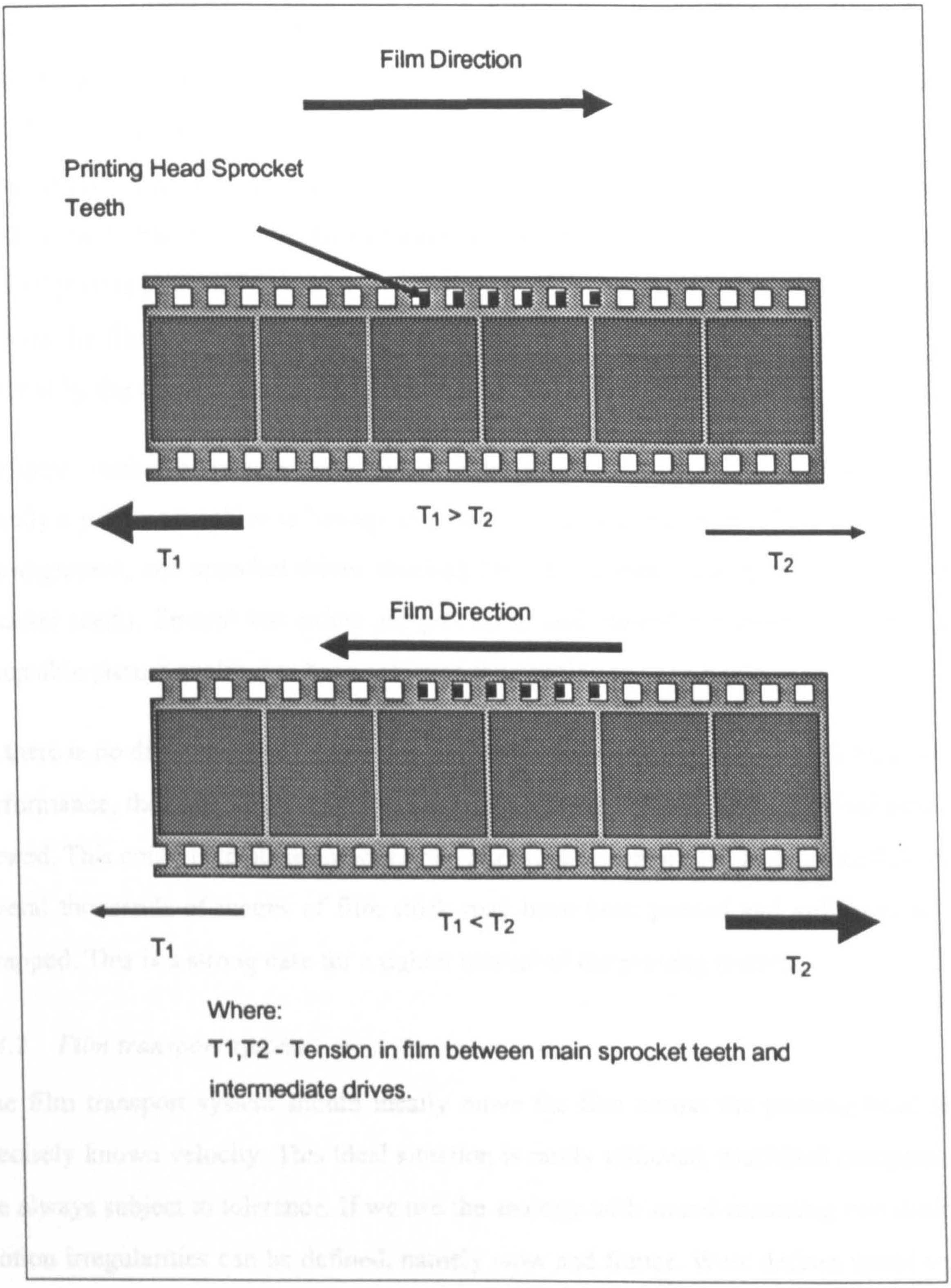

Figure 1.6 - Film registration by tension differential

printing cycle [Stoker, 1987]. The tests carried in this 1987 report used high-speed imaging of film as it passed over a printing aperture. Tests were very successful in obtaining quantitative information on the point movement of the film. This gave useful information on random 'flutter' movements such as judder and movement pertaining to sprocket picking. It was found that for a single strand of film the maximum movement across the width of the film had a calculated value of 0.38 mm (accurate within +/- 0.03 mm). This figure for maximum deviation over 5 frames of film or 20 perforations could be compared with the maximum tolerance of +/- 0.381 mm over the length of 100 perforations quoted by the American National Standards Institute (PH.22-119). Because the final print is projected onto a large viewing screen the movement that can be tolerated between the films has to be relatively small if no noticeable film unsteadiness is to be detected by the viewer.

The identification of picture unsteadiness is by direct viewing of the processed print. Initially a printing machine is 'set-up' (i.e.. tension pre-set, transport rollers checked for mis-alignment, and sprocket drives checked for film perforation alignment and dirt on sprocket teeth). Several test prints are processed and viewed for steadiness. Once an acceptable picture quality has been achieved the printing run can begin.

As there is no direct feedback of tension or film speed and therefore no check on system performance, the only way a machine can be seen to be faulty is when the final print is viewed. This could take place an hour or so after it has been printed and during this time several thousands of metres of film stock may have been printed and will have to be scrapped. This is a strong case for a tighter control of the printing process.

1.4.2 Film transport system

The film transport system should ideally move the film across the printing head at a precisely known velocity. This ideal situation is rarely achieved; machined components are always subject to tolerance. If we use the analogy with sound-recording two distinct motion irregularities can be defined, namely wow and flutter. Wow defines speed variation at low frequency, while flutter describes those at higher frequency. In film printing the low frequency speed variations are usually sinusoidal, caused by non-concentric rollers or the build up of dirt. This unsteadiness can readily be seen by using a stroboscope during the running of the film through the printing machine. Short-term velocity variations or flutter can be further sub-divided into two categories:

- ☐ Those which are uniform across the width of the film, so the instantaneous velocity is the same at all points.
- ☐ Irregular variations which are not uniform across the film.

The control and elimination of these variations is notably difficult to achieve using conventional servo control.

The main sources of flutter are:

- ☐ Tension variations in the film.
- ☐ From poorly set or machined transport rollers causing the edge of the film to rub against the shoulder of the roller, this is commonly known as 'edge picking'.

Low-frequency speed variations are one of the main problem areas in the printing process. The main result of these low frequency speed variations is density bars; this is the effect that occurs on developed film due to speed variation over the illuminated printing aperture. These density bars occur at frequencies below 20 Hz.. The main sources of these low frequency disturbances are:

- ☐ Eccentricities in the capstan or associated drive; these produce uniform velocity of the drive surface with corresponding variations in film velocity. This modulation effect is common to many film transport devices [Soluk, 1986] and the specifications found on many systems quote a maximum relative movement compared to the height of the 35mm frame to be 0.13%. i.e.. $\frac{Relative\ Movement}{Height\ of\ frame} = 0.13\%$
- ☐ Vibration of free lengths of film between drives, the natural frequency of film is typically around 20-25 Hz..

It is also noticed in the film laboratory that these low frequency disturbances occur less at the higher printing speeds such as those found on panel printers used for film duplication.

1.4.2.1 Winding systems

One of main causes of unsteadiness in any film transfer situation is the winding or reeling system. The disturbance from the reeling system is mainly due to the response time of the servo systems. The greater the inertia of the film reel, the more power is needed to respond to a disturbance. Many solutions have been used to overcome this problem. Soluk in his paper on film dynamics on telecine machines recommends using *"free-standing core take-up, and whenever possible, avoid large film rolls"*. One successful system used at Technicolour in the USA uses large negative loops to buffer the effects of winding system from the printing area. This has enabled Technicolour to reach printing speeds of 5m/s (1000 ft/min.) [Michelson].

1.4.3 Film properties

The findings described above are based using Eastman Kodak 35 mm acetate film. Nowadays polyester film has emerged as a substitute base for film printing. This is due to its wear resistance properties, although acetate film is still used due to the fact that polyester film tends to generate static electricity which can attract dust into the printing area. Added to this problem of different film type there is also the problem of each manufacture's film having different physical properties. Appendix B describes tests made to determine the physical characteristic properties of 35 mm motion picture film. The results from these tests show a marked difference in damping and stiffness coefficients between film types and also between film stock manufacture. This problem has not been addressed in the design and production of present day sprocket film drive systems.

1.4.4 Sprocket design

The drive system of existing printing machines relies on sprocket design as well as the accuracy of the perforations. Figure 1.7 shows a section from a drive sprocket with the film under ideal conditions, that is all teeth are drivers and that the pitch of the film is identical with that of the sprocket. It has been shown that this occurs very rarely, mainly due to sprocket design and the physical properties of the film [Jones, 1923]. The design of sprocket drives has overlooked varying ages of the film and the quality if the film as it passes though its various processes including printing, developing and drying. These processes result in a variation in pitch ranging from about 0.2% swell to approximately 3% shrinkage. Jones indicated in his paper that a large number of laboratory wear and tests

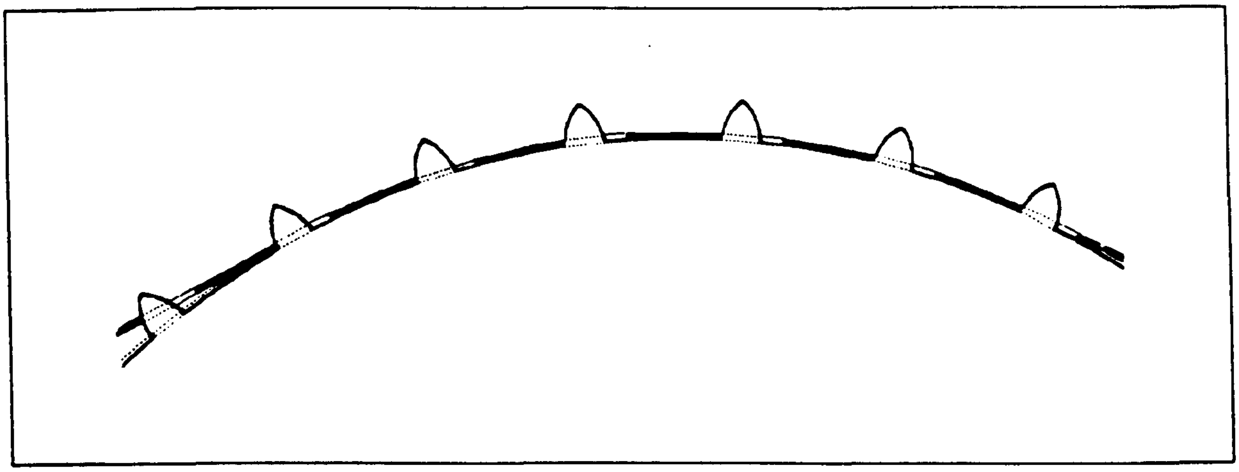

Figure 1.7 - 'Ideal' film registration

had shown that with the sprockets now in use, least destructive effect is shown when the film being run has shrunken or has a shorter pitch than the actual pitch of the sprocket.

1.4.5 Tensioning devices

Film tension is an important criterion, related to the properties of the particular film in use. Too much tension will allow the film to distort to an unacceptable level which will ultimately cause excessive wear from the drive sprockets. Too little tension will cause loss of registration on the drive sprockets. The tensioning device currently used in most printing machines consists of a tension arm and transport roller configuration which can be pre-set at different tensions by the adjusting the position of a spring stop. Once set, the tension applied to the film during a print run cannot be changed.

There are two functions of this device. The first and most obvious function is the ability to set the running tension of the film. The second function is to use the inertia of what is essentially a spring-mass-damper system to damp out any unwanted film vibrations. It could be said that this system is used to try and hide the problem of film unsteadiness. The addition of this mass between the drives would have the effect of decreasing the band-width of any servo system that might be installed on conventional machines to control tension and speed of the film. For that reason we have dispensed with this inflexible system of film tensioning.

1.5 Analogous Processes

There are many different processes that in some way or another embody some of the principles involved in film copying. A data search has identified three main areas that have yielded useful information for this research.

1.5.1 Magnetic tape-transport mechanisms

One of the processes most analogous to film printing is that of magnetic tape recording and playback systems. Unlike the film printing process the tape transport system has only one transport drive. The reproduction of quality sound makes the design of the drive mechanism together with the control system very important.

The operating modes for continuous-running tape transport systems have many variations. The ones of most interest are the forward search, under the control of a special high-speed capstan and the forward play mode.

1.5.1.1 Machine types

One of the early types of tape transport which might ideally suit the film transport scheme is the "straight-through" tape path shown schematically in figure 1.8. Three motors are used in this scheme, two for the supply and feed reels and one for the capstan drive. The supply and feed motors are torque controlled while the capstan motor is a synchronous motor whose speed is governed by the frequency of the power supply.

The control of this type of system is fairly crude with the tension being maintained by the feed and take-up reels and the speed governed by the capstan roller. The tension arm and the right most idler are used to smooth out rapid variations in tension of the tape as it comes from the supply reel. Small tension fluctuations result from torque pulses from the control of the supply reel. The main cause of tension variations is the lack of concentricity of the tape reels.

In this system the amount of tape on each reel will influence the tension applied by the reel motors. In normal operating conditions, controls applied to the reel motors are adjusted so that the motor torques balance when half the tape is on each reel, the supply reel applying torque in the direction opposite to the direction of tape motion. The tension

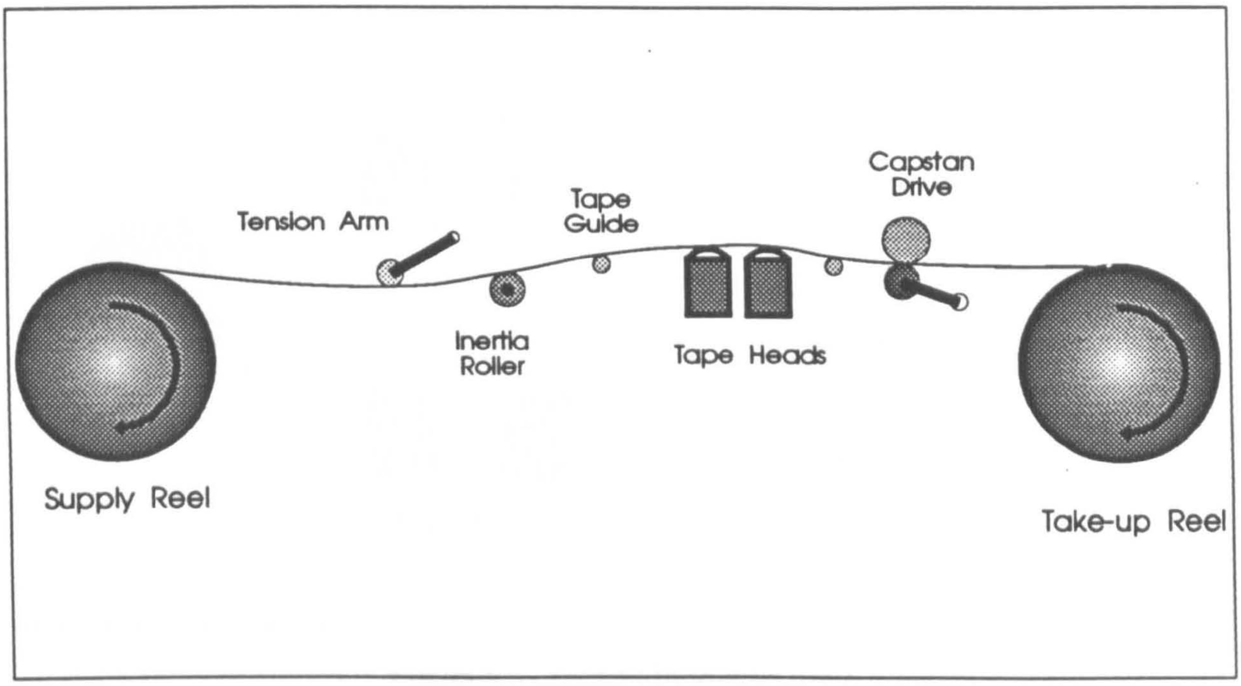

Figure 1.8 - "Straight-through" tape transport system

variations encountered during the operation of this type of machine are undesirable and cause flutter and other irregularities of tape motion.

Because of this tension variation, any slippage at the capstan will result in speed fluctuation. Heavy pressure on the capstan pinch roller is used to avoid this. This in turn increases the load on the capstan motor and results in small speed variations due to the distortion of the rubber coating of the pinch roller.

The tension fluctuations also cause the tape to stretch, which affects the speed of the film as it passes over the heads.

The need for better quality recordings led to the design of the closed-loop drive. The schematic diagram shown in figure 1.9 shows this drive and its principal elements. The tape enters the closed loop over a capstan pinch roller assembly. It then passes over one set of heads, around a turn-around idler, and then back over another set of heads. It finally leaves the loop via the same capstan with another pinch roller.

If there is no slippage at either point of contact on the capstan initial tension in the loop will be maintained. This type of system also minimises the amount of unsupported tape reducing tape resonance effects.

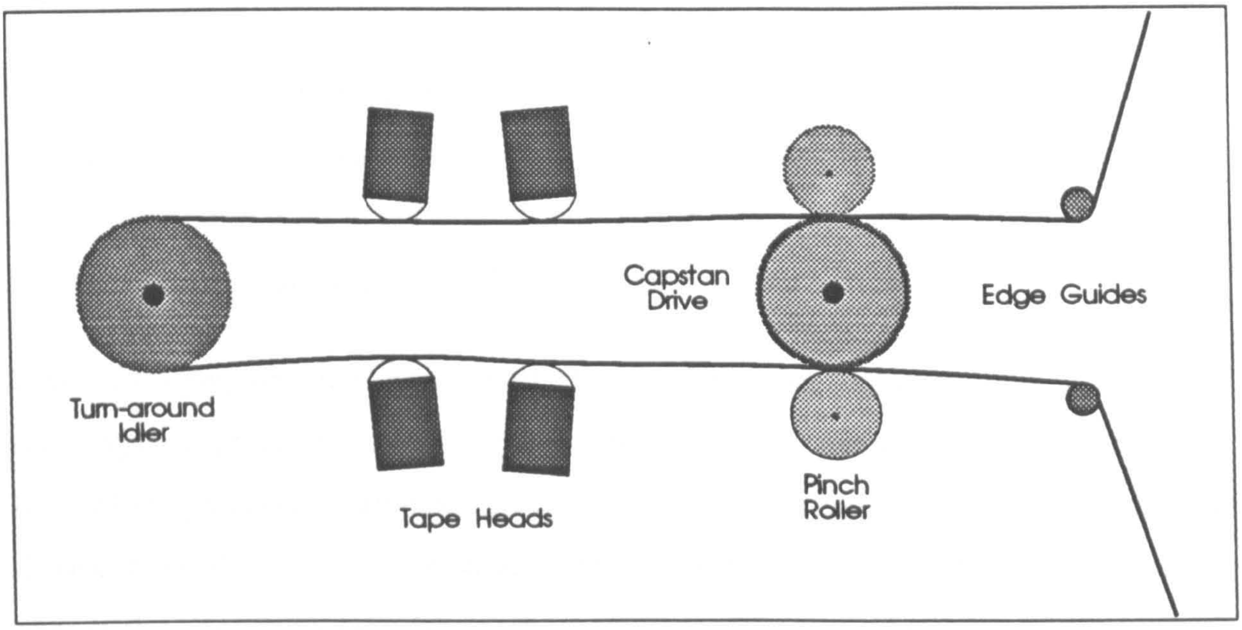

Figure 1.9 - Closed-loop tape drive

To reduce further the chance of any tension variations each feed and take-up motor is controlled by a separate servomechanism which maintains constant tension in the tape external to the loop.

Two main methods of servo feedback have been used in these winding systems:

- ☐ A movable arm (dancer arm) carrying a transport roller over which the tape passes. The position of this arm is related to the tension in the tape.

- ☐ The other system uses a follower arm resting on the reel to sense the amount of tape on it. This information can be used to alter the torque of the reel motor to maintain constant tension.

Two types of reel control that are commonly used are:

- Mechanical - The tension feedback signal actuates a mechanical brake which controls the effective torque delivered to the reel.

- Electrical - The sensing signal is used to directly control the torque delivered to the motor.

1.6 Aims and Objectives of the Research Programme.

The aims and objectives can be divided into three main areas. These main areas suggested the logical sequence for the progress of the research project undertaken.

1.6.1 Development of capstan drive system.

The use of sprocket drives, as discussed previously in this chapter limits the performance of film transport. Sprockets rely on film perforation accuracy and by the nature of film conveyance cause wear to the film at these points. Gears and cams have the problem of backlash and are relatively inflexible for complex motion profiles.

Detailed investigation has been carried out into the existing problems of unsteadiness and other types of processes that involve the transport of web material have been examined. Most of the processes examined involve the use of some type of capstan or pinch roller drive system. These varied from large scale systems such as newspaper printing to smaller ones such as computer tape drives where accurate stopping and starting of the magnetic media are essential.

A film drive system that incorporates direct driven capstan rollers controlled entirely by digital control systems is the objective of this section of the research.

Complex motion profiles together with elaborate control algorithms can be designed and implemented in software. This gives the system a more accurate transport drive together with the flexibility to change control strategies and motion profiles without major mechanical work.

1.6.2 Simulation and control system design

The simulation of the physical system is a standard analysis tool used in the evaluation of hardware prior to actual construction. Similarly the design and testing of control strategies can be undertaken without the need to resort to physical testing. However the models that are developed are always slightly different from the actual system and some of the components of the system will have unknown parameters or noise associated with them.

The objective of this area of the research has been to develop a procedure for model validation in order to improve model accuracy. This included physical testing of components using various experimental tools such as frequency response analysis for system identification.

Two types of model were constructed. The first included detailed descriptions of the various components of the system, described by time dependent, non linear differential equations and transfer functions. Non-linear effects, sensor noise, external disturbances were incorporated to produce a very good representation of the physical system.

The second model was a reduced order linearised version of the first one. This enabled the system to be described in state-space form. In this form control system design was readily accomplished using one of the available control system design software packages. Resulting control strategies could then be tested with the linear model description and finally with the non-linear description of the plant to test for controller robustness.

1.6.3 Transputer implementation.

The control algorithms resulting from the design stage can be expressed as a set of difference equations. The control strategies involved many different components including Kalman filters and matrix manipulation. Along with these control algorithms data input and output must be implemented. Using conventional single processor systems, which rely on sequential computation structures, was seen to be too slow for the system specification. It was decided to use parallel processing techniques by implementing the control system on an array of transputers.

Using the developed control structure the aim was to extract components of the design that could be performed concurrently by placing them on separate processors. The objective was to reduce computation times and to maximise system performance. In the following chapters it can been seen that the block diagram description of control systems can be used as a basis for the building of high performance digital control systems. Another aim of this section of research was to show the development of the control system model into a process model described by data flow diagrams. This process model could be developed on a single transputer using time slicing of concurrent processes and by describing data flow channels in the abstract. Once the process model had been validated, individual processes could be easily placed onto separate processing elements and a reduction in computational time achieved.

Statement of Originality

The arguments within the film industry to retain sprocket drive systems even though numerous papers have been written describing the effects on the film and the final picture quality have been long standing. Technology has been available in the sound recording field for many years enabling an improved method of transport. New control and measurement systems have been developed and can now be realised due to the advent of fast, cheap microprocessors and parallel processing techniques.

The system developed in this study is unique in the area of motion picture processing. The simulation studies carried out have enhanced the development of future film processing machines.

Parallel processing techniques applied to this 'real-time' problem illustrate how short computation times can be achieved on relatively complex control algorithms, leading to accurate control of film transport systems well beyond any current system available today.

Summary

This chapter has introduced the fundamentals of the workings within the film printing laboratory. It has specifically focused on the mechanism of printing large quantities of motion picture release print. Problem areas have been identified and analogous processes have been described with the aim of combining some of their ideas and technology to improve the film printing process.

A brief overview of the project objectives and aims has identified three main components for research and further chapters will expand on them in more detail.

The next chapter is intended to review control theory that will be used to develop and finally implement the control systems for controlling some of the film printing processes.

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Chapter 2

Review of Control Theory.

2.1 Introduction

Two methods of control design were considered in this project. "Classical control" developed in 1940's uses Laplace or Fourier transform representations of n^{th} order differential equations derived from system dynamics and control specification . State-space formulation which dates from the 1960's represents an n^{th} order system by a set of n first-order differential equations. The essential difference between these two methods is in their design procedure. The end result, for a digital controller is a set of difference equations, for both routines.

Many of the control design problems associated with single-input single-output systems (SISO) are based on a mathematical model of the physical system and expressed as transfer functions. These can be dealt with using classical design procedures. Control system design can proceed in systematic fashion using Nyquist and root locus theory. Systems of any order can be handled with this theory, but in practice many higher order models are which are dominated by the dynamic effects of first,second or third order systems can be adequately described by reduced order models [Owens 1986].

Classical design methods have been widely used in the determination of system transfer functions. Typically these are obtained from frequency response testing [Stanway 1986]. This was essential where unknown parameters existed that would not allow the formulation of the plant description by conventional means or where validation/verification was required.

State-space methods of controller design are really the only way to design controllers for multi-input multi-output (MIMO) systems. They can deal with system descriptions of any order being well suited for the computer [Franklin et al., 1990] and can be used to obtain results for high-order or MIMO systems that are difficult to handle with classical methods.

One of the main problems in designing a MIMO type of system is the interaction between separate control loops in the process.

These MIMO systems cannot be de-coupled due to the interaction between the various elements of the system. A controller has to be formulated that takes into consideration the total system response. The problem is to design a regulator that keeps the output variables near to constant, prescribed values. One technique is to choose the controller feedback gains according to some performance index [Grimble 1986]. The resulting controller is often called optimal. These optimal control solutions differ from classical control methods in that they take into account noise and disturbance inputs providing a controller with a degree of "robustness".

Classical control algorithms such as proportional (P) integral (I) and differential (D) have been used with some success in motor drive applications [Abdel-Azim et al., 1979]. Abdel-Azim reported that the servo control for a video tape transport system based on PID control had some success but was affected by external disturbances from tape tension fluctuations. Abdel-Azim concludes the paper by recommending the use of a more sophisticated controller design to eliminate these unwanted external disturbances.

One such design is the Linear Quadratic Regulator (LQR). This design methodology, differs from classical techniques which aim to obtain a specific transient response, and endeavours to minimise the control energy required to keep the mean square-error response of the system as small as possible. This method has the advantage of involving a state estimator known as the Kalman filter, and as commented by Grimble "*has proved itself in applications and may be extended to achieve parameter estimation or to allow the presence of non-linearities in the system*", but in aircraft use it has caused a degree of instability [Bryson, 1978].

2.2 Control Law Design Using State-Space Methods

This has concerned both MIMO and SISO types of system based on well known types of control strategy. The approach has been to design a continuous controller then to transform this to its discrete equivalent. This emulation approach has employed the use of computer aided system design (CASD) packages, whose operation relies mainly on the state space method of system representation. This has allowed the remaining controller design to use the direct digital design method [Franklin et al., 1989]. Franklin [1989, pp 238-239] discusses the advantages of state space design over classical methods and points out that the final control equations, given the same set of specification equations, should be very similar if not identical.

2.2.1 System description

The system to be controlled is described by a set of equations of motion. This description of the continuous system in state-space form is given by,

$$\dot{\mathbf{x}} = \mathbf{A}\,\mathbf{x} + \mathbf{B}\,\mathbf{u} \tag{2.1}$$

and,

$$y = C\,\mathbf{x} \tag{2.2}$$

Where,

$$\mathbf{A} \in \mathrm{R}^{\,n \times n}, \mathbf{B} \in \mathrm{R}^{\,r \times n},\; C \in \mathrm{R}^{\,n \times o}$$

n - number of states, r - number of controls, o - number of outputs

If we assume that control is applied from the microprocessor via a zero order hold (ZOH) device such as a digital to analog converter (DAC). Then (2.1) and (2.2) can be represented by the exact discrete equivalents, given by,

$$\mathbf{x}\,(k+1) = \mathbf{\Phi}\,\mathbf{x}\,(k) + \mathbf{\Gamma}\,\boldsymbol{u}\,(k) \tag{2.3}$$

$$y\,(k) = \mathbf{H}\,\mathbf{x}\,(k) \tag{2.4}$$

The first approach in designing a controller is to assume that all states and outputs are measurable. In a 'real' system this might not be the case as will be seen later. This assumption allows for the formulation of a control law that can be tested on the plant model as discussed in chapter 4.

2.2.2 *Regulator Design*

The first step in the regulator design assumes that there is no reference input, $r = 0$ [Franklin et al. 1986, pp. 327]. This first assumption leads to a control law that is simply the feedback of a linear combination of all the state elements, given by,

$$u = -\mathbf{K}\,\mathbf{x} = -[\ K_1\ K_2\ \ldots]\begin{bmatrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ \cdot \end{bmatrix} \tag{2.5}$$

Substituting (2.5) in the difference equation (2.3), gives

$$\mathbf{x}\,(k+1) = \mathbf{\Phi}\,\mathbf{x}(k) - \mathbf{\Gamma}\,\mathbf{K}\,\mathbf{x}(k) \tag{2.6}$$

The z-transform of (2.6) is

$$(z\mathbf{I} - \mathbf{\Phi} + \mathbf{\Gamma}\,\mathbf{K})\,\mathbf{X}(z) = 0 \tag{2.7}$$

The system with this control law has a characteristic equation of the form,

$$\det\left|\, z\mathbf{I} - \mathbf{\Phi} + \mathbf{\Gamma}\mathbf{K} \,\right| = 0 \tag{2.8}$$

This structure of this control law by its nature, *(r=0)*, drives all states to zero. The next section describes the introduction of a reference input.

2.3 Controller design with reference input

The introduction of reference inputs to a system is the next step towards a more realistic control system [Franklin et al 1989]. Franklin et al. [1989, pp 273] considers the nature of inputs and shows how a good transient response is obtained for the system to these inputs. The first stage of this type of controller design is to understand how the reference inputs are introduced into the system, and then how the steady state of the system is effected using this type of control strategy. The following stages deal with two methods for reducing steady-state control for one or more outputs. Finally the case where states are not available or contain too much noise is discussed together with a suitable solution.

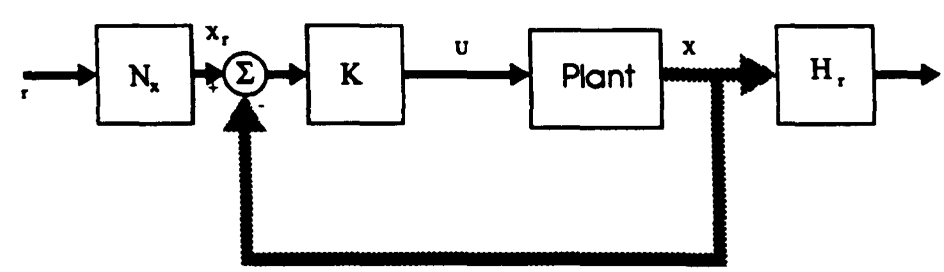

Figure 2.1 - Full-state feedback

2.3.1 Full-state feedback

The structure of this type of system is shown in figure 2.1. It has a state command matrix $\mathbf{N_x}$ that defines the desired value of the state, $\mathbf{x_r}$. The problem is to obtain the matrix $\mathbf{N_x}$ so that the system output, $\mathbf{y_r}$ (determined by $\mathbf{H_r}$), is identical to the desired reference value. The only assumption here is that the number of inputs to the system, $\mathbf{u}$, is the same as the number of desired outputs, $\mathbf{y_r}$. This will give us a unique and exact answer.

In determining $\mathbf{N_x}$ we must understand its function. Basically it transforms the reference values $\mathbf{r}$, to the reference states, $\mathbf{x_r}$. This value of $\mathbf{x_r}$ can be determined from the equilibrium state for each reference $\mathbf{r}$.

This allows us to define $\mathbf{N_x}$ so that

$$\mathbf{N_x}\,\mathbf{r} = \mathbf{x_r} \text{ and } \mathbf{u} = -\mathbf{K}\,(\mathbf{x} - \mathbf{x_r}) \tag{2.9}$$

From the system specification we calculate what the states should be at equilibrium for the desired outputs.

2.3.2 Pole placement

This method aims to select control gains to give adequate damping and speed of response to the modes of the closed-loop system. Franklin [1986, pp 336] has documented the selection of these gains for systems of up to 6th order.

If the control input is a fixed linear function of the state vector,

$$u = -\mathbf{K}\mathbf{x} + \mathrm{U}_{ref} \tag{2.10}$$

where U_{ref} is an external reference input signal, then the dynamics of the closed-loop system are,

$$\dot{\mathbf{x}} = (\mathbf{A} - \mathbf{B}\mathbf{K})\,\mathbf{x} + \mathbf{B}\mathrm{U}_{ref} \tag{2.11}$$

It is clearly seen that the nature of the response is dependent on **(A - BK)**. The eigenvalues of **(A - BK)** give the frequency and damping of various modes of the system, while the corresponding eigenvectors give the mode shapes. In the pole-placement technique, the gain matrix **K** is selected so that all the modes of the system have the desired frequency and damping.

2.3.3 Optimal control

The control-design procedures dealt with so far have only been applied to SISO systems. If we try and apply such techniques as pole placement we find the feedback gains are not uniquely determined by the resulting equations.

One form of optimal control, Linear Quadratic (LQ) synthesis, aims to minimise the control energy required to keep the error response of the system as small as possible. The design parameters are weightings or penalties on deviations of states and controls. Optimal or LQ control is inherently a MIMO linear system control design method although most of its applications are MISO. It has also been applied to many non-linear control problems [Franklin, 1981]. Frankiln [1981, pp.108] points out that this method of system control has been mainly limited to simulation studies. Applications through actual implementation are not widely found.

The design of control systems using this technique is obtained using specific performance factors. These factors or performance indices are based upon engineering experience and the judgement of the design goals required of the system [STC Inc., 1991].

We wish to implement this solution at steady-state which would yield constant gain. This leads to a solution called the Linear Quadratic Regulator, or LQR, because it applies to linear solutions. Given the discrete plant, see (2.3), (2.4), the quadratic cost function given by,

$$J = \frac{1}{2}\sum [\mathbf{x}^T(k)\,\mathbf{Q}_1\,\mathbf{x}(k) + \mathbf{u}^T(k)\,\mathbf{Q}_2\,\mathbf{u}(k)] \tag{2.12}$$

is to be minimised where,

$$\Phi \in R^{\,n \times n}, \Gamma \in R^{\,r \times n}, \; H \in R^{\,n \times o}$$

n - number of states, r - number of controls, o - number of outputs

$\mathbf{Q}_1, \mathbf{Q}_2$ are symmetric and positive semi-definite weightings i.e.

$$\mathbf{Q} = \mathbf{Q}^T = \mathbf{0}$$

The result of this minimisation is the linear constant feedback law.

$$\mathbf{u}(k) = -\mathbf{K}\mathbf{x}(k) \tag{2.13}$$

where

$$\mathbf{K}(k) = [\mathbf{Q}_2 + \Gamma^T \mathbf{S}_{ss}(k+1)\Gamma]^{-1}\,\Gamma^T \mathbf{S}_{ss}(k+1)\Phi \tag{2.14}$$

$\mathbf{S}_{ss}$ is the steady state solution to the discrete algebraic matrix Riccati equation.

2.3.4 *Selection of weighting matrices* Q1 *and* Q2

The selection of $\mathbf{Q}_1$ and $\mathbf{Q}_2$ is usually a matter of trial and error linked with an understanding of the control problem. One approach has been formulated [Bryson,Ho, 1975] which allows initial estimates of these weighting matrices to be made. Bryson's rule (2.15) and (2.16) provides initial estimates of the weightings so as to limit the state deviation and control deflections to some desired values.

The approach is to take $\mathbf{Q}_1 = \mathbf{H}^T \overline{\mathbf{Q}}_1 \mathbf{H}$ so that the states enter the cost via the important outputs and to select $\overline{\mathbf{Q}}_1$ and $\mathbf{Q}_2$ to be diagonal with entries so selected that a fixed percentage change from the maximum value of each variable makes an equal contribution to the cost.

$$Q_{1,i}=\frac{1}{m_i^2} \tag{2.15}$$

$$Q_{2,i}=\frac{1}{u_i^2} \tag{2.16}$$

where m_i is the maximum desired deflections of the output and u_i is the maximum desired deviation of the control u.

2.4 Steady-state control

Two methods of steady-state control can be implemented.

2.4.1 Feedforward control

This type of steady-state control involves the introduction of an extra control term that is proportional to the reference input, see figure 2.2, namely,

$$\mathbf{u}_{ss}=\mathbf{N}_u\,\mathbf{r}, \tag{2.17}$$

The steady state requirements for the system are,

$$\mathbf{N}_x\,\mathbf{r}=\mathbf{x}_r=\mathbf{x}_{ss} \tag{2.18}$$

$$\mathbf{H}_r\,\mathbf{x}_{ss}=\mathbf{y}_r=\mathbf{r}$$

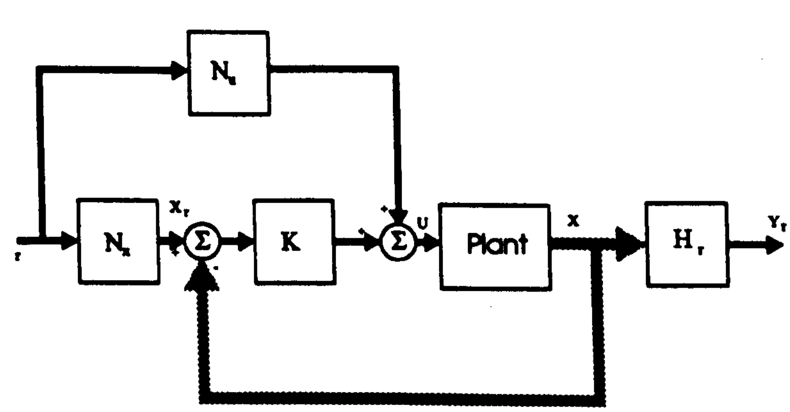

Figure 2.2 - State feedback with reference feedforward

this reduces to,

$$\mathbf{H}_r \mathbf{N}_x \mathbf{r} = \mathbf{r} \quad \textit{thus} \quad \mathbf{H}_r \mathbf{N}_x = \mathbf{I} \tag{2.19}$$

With this extra term we assume the system is in steady state, which gives,

$$\mathbf{x}(k+1) = \mathbf{\Phi}\,\mathbf{x}(k) + \Gamma\,\mathbf{u}(k) \Rightarrow \mathbf{x}_{ss} = \mathbf{\Phi}\,\mathbf{x}_{ss} + \Gamma\,\mathbf{u}_{ss} \tag{2.20}$$

or

$$(\mathbf{\Phi} - \mathbf{I})\,\mathbf{x}_{ss} + \Gamma\,\mathbf{u}_{ss} = 0 \tag{2.21}$$

from (2.17) and (2.18),

$$(\mathbf{\Phi} - \mathbf{I})\,\mathbf{N}_x \mathbf{r} + \Gamma\,\mathbf{N}_u \mathbf{r} = 0, \tag{2.22}$$

reducing to

$$(\mathbf{\Phi} - \mathbf{I})\,\mathbf{N}_x + \Gamma\,\mathbf{N}_u = 0. \tag{2.23}$$

Collecting (2.19) and (2.23) into one matrix equation

$$\begin{bmatrix} \mathbf{\Phi} - \mathbf{I} & \Gamma \\ \mathbf{H}_r & 0 \end{bmatrix} \begin{bmatrix} \mathbf{N}_x \\ \mathbf{N}_u \end{bmatrix} = \begin{bmatrix} 0 \\ \mathbf{I} \end{bmatrix} \tag{2.24}$$

yields the desired result

$$\begin{bmatrix} \mathbf{N}_x \\ \mathbf{N}_u \end{bmatrix} = \begin{bmatrix} \mathbf{\Phi} - 1 & \Gamma \\ \mathbf{H}_r & 0 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ \mathbf{I} \end{bmatrix} \tag{2.25}$$

2.4.2 Integral control

Feedforward is not often used by itself because its value depends on accurate knowledge of the plant gain. The preferred method of reducing steady-state errors is to use integral control or possibly to combine integral with feedforward control.

The addition of an integral term to the plant model has the effect of adding an integral state to the existing output. This new augmented model is then used to design the control law. The new control law will comprise gains from pre-existing state elements plus the

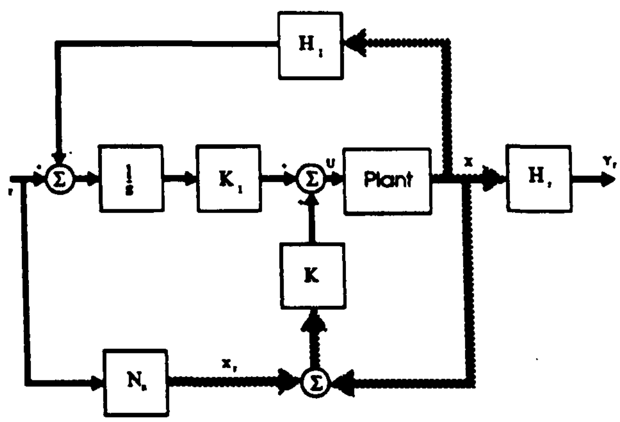

Figure 2.3 - Integral Control with Full-state Feedback

output integrator. The integrator must be added into the controller part of the system as it does not exist in the plant. For the system described by,

$$\mathbf{x}(k+1) = \mathbf{\Phi}\,\mathbf{x}(k) + \mathbf{\Gamma}\,\mathbf{u}(k) \tag{2.26}$$

$$y(k) = \mathbf{H}\,\mathbf{x}(k) \tag{2.27}$$

we augment the state with x_I, which obeys the difference equation

$$x_I(k+1) = x_I(k) + y(k) = x_I(k) + \mathbf{H}\,\mathbf{x}(k). \tag{2.28}$$

Collecting (2.26) together with (2.28) gives the augmented plant model

$$\begin{bmatrix} x_I(k+1) \\ \mathbf{x}(k+1) \end{bmatrix} = \begin{bmatrix} 1 & \mathbf{H} \\ 0 & \mathbf{\Phi} \end{bmatrix} \begin{bmatrix} x_I(k) \\ \mathbf{x}(k) \end{bmatrix} + \begin{bmatrix} 0 \\ \mathbf{\Gamma} \end{bmatrix} u(k). \tag{2.29}$$

The resulting control law is given by,

$$u(k) = -[K_I\,\mathbf{K}] \begin{bmatrix} x_I(k) \\ \mathbf{x}(k) \end{bmatrix} \tag{2.30}$$

With this new system definition, the design techniques discussed in the next section can be used. They will result in the control structure shown in figure 2.3 for the full-state feedback case.

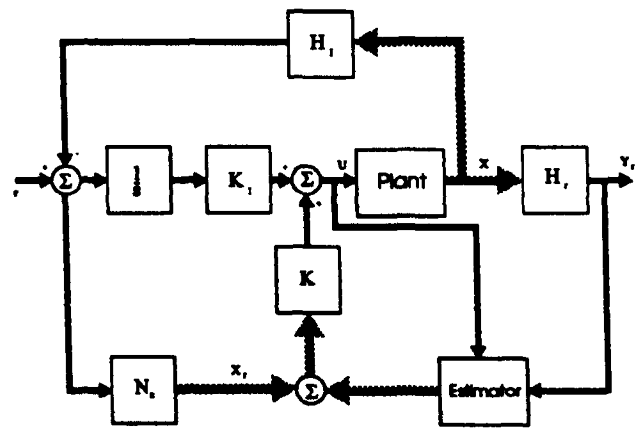

Figure 2.4 - Estimator with full-state feedback

2.5 Estimator Design

The control law designed in the last section assumed that all state elements were available for feedback. Because typically, not all elements are measured, the missing portions of the state need to be reconstructed for use in the control law.

We will look generally at the estimator design but later will concentrate more fully on one particular design of estimator, the Kalman filter.

The idea behind the estimator will be to let $u = -\mathbf{K}\hat{\mathbf{x}}$ or $u = -\mathbf{K}\bar{\mathbf{x}}$, replacing the true state used in (2.26) by its estimate. This will provide the missing states as well as providing an improved measurement which is often contaminated with noise, e.g film tension fluctuations. The resulting control structure is shown in figure 2.4.

To minimise computational delays and improve accuracy we wish to base our current estimates $\hat{\mathbf{x}}$ on the most current value of the measurements $y(k)$.

This current estimator has the form,

$$\hat{\mathbf{x}}(k) = \bar{\mathbf{x}} + \mathbf{L}\,(y\,((k) - \mathbf{H}\,\bar{\mathbf{x}}(k)), \tag{2.31}$$

where $\bar{\mathbf{x}}(k)$ is the predicted estimate based on a model prediction from the previous time estimate given by,

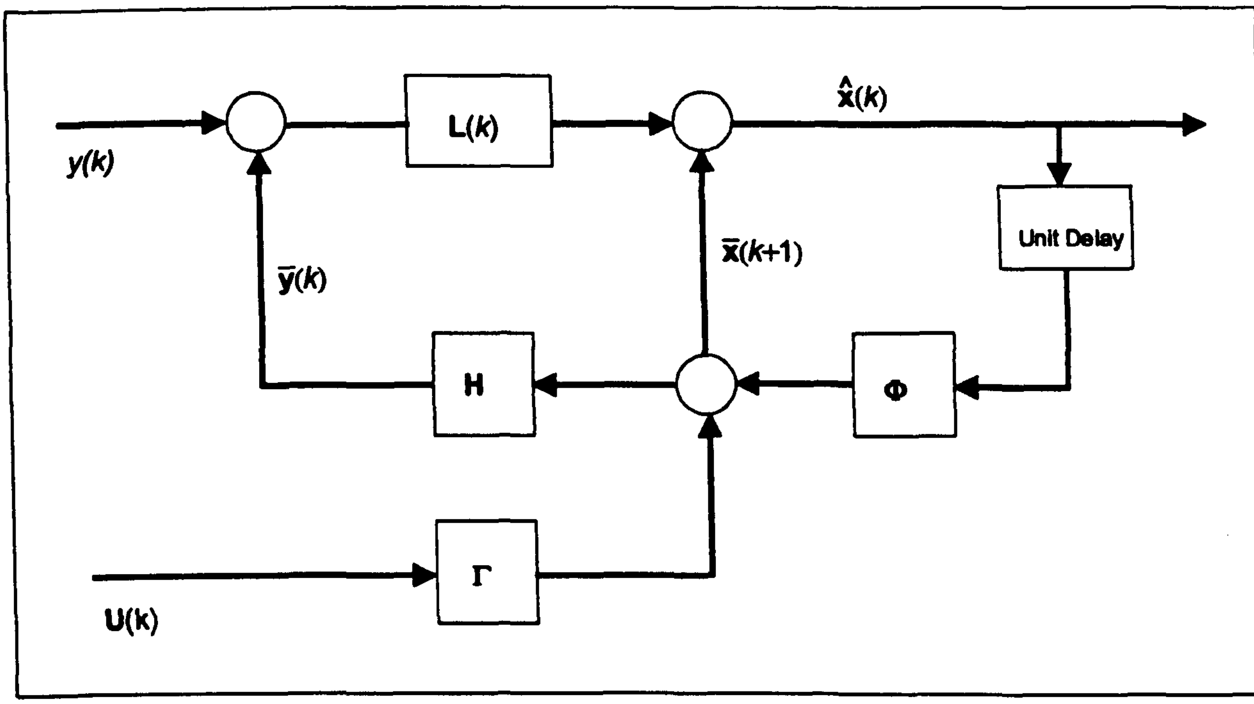

Figure 2.5 - Block representation of Kalman filter

$$\bar{\mathbf{x}}(k) = \Phi\,\hat{\mathbf{x}}(k-1) + \Gamma u(k-1). \qquad (2.32)$$

2.5.1 Optimal estimation

A method for calculating the L-matrix in the equations for the current estimator is to use optimal estimation or a "Kalman filter". To implement a constant gain in the controller a constant-gain Kalman filter will be used. This assumes a known level of measurement noise for estimate error minimisation.

2.5.2 The Kalman filter

Consider the plant given by the discrete description,

$$\mathbf{x}(k+1) = \Phi\mathbf{x}(k) + \Gamma\mathbf{u}(k) + \Gamma_1\,\mathbf{w}(k) \qquad (2.33)$$

$$y(k) = \mathbf{H}\mathbf{x}(k) + \mathbf{v}(k) \qquad (2.34)$$

where the process noise **w***(k)* and measurement noise v*(k)* are random sequences with zero mean, ("white" noise). These covariances or noise levels are defined by $\mathbf{R}_w$ and $\mathbf{R}_v$ respectively.

If the form of the current estimator is as above (2.31), the aim is to pick **L** so that the estimate of **x***(k)* is optimal.

The best estimate $\hat{\mathbf{x}}$ of the state at time k, based on measurements up to time k-1 can be denoted by $\bar{\mathbf{x}}(k+1)$, see figure 2.4.

If we assume that somehow we have a prior estimate $\bar{\mathbf{x}}(k)$ of the state at the time of measurement, one-step ahead prediction, we must update this estimate based on current measurements, ie.

between measurements (time update):

$$\bar{\mathbf{x}}(k+1) = \mathbf{\Phi}\hat{\mathbf{x}}(k) + \mathbf{\Gamma}\mathbf{u}(k) \tag{2.35}$$

and at the measurement time (measurement update):

$$\hat{\mathbf{x}}(k) = \bar{\mathbf{x}}(k) + \mathbf{L}\,(\,y(k) - \mathbf{H}\,\bar{\mathbf{x}}(k)) \tag{2.36}$$

Where the steady-state Kalman filter gain can be expressed as,

$$\mathbf{L}(k) = \mathbf{M}(k)\,\mathbf{H}^T(\mathbf{H}\,\mathbf{M}(k)\,\mathbf{H}^T + \mathbf{R}_v)^{-1} \tag{2.37}$$

where **M** is the expected mean square error of the state estimate, $\bar{\mathbf{x}}(k)$, before the measurement.

Summary

This chapter has reviewed theory that will be used to design, simulate and finally implement a control solution. We have seen that with the use of computer aided-design packages much of the tedious design work can be taken away, but it is still up to the designer to asses the results from the various tested control strategies.

The use of the state-space notation in many of the design packages has led us to follow this approach when designing the controllers. It has also been shown that similar control equations can be derived using both classical and state-space design methods. The design of controllers using state-space methods has the advantage that it can readily deal with multi-input multi-output systems.

Two methods of state space design dealing with steady state control have been discussed. Full-state feedback, where all the states of the system can be readily measured, and estimator design, where not all the states can be measured or are contaminated by noise. An estimator design based on the kalman filter has been described and a set of control algorithms formulated. It can be seen from these that much computation is needed to implement them in a 'real' system and it was pointed out that many of these control strategies have only been implemented in the simulation stage for this reason.

The next chapter introduces a computational device that will overcome this limitation, the transputer.

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Chapter 3

Transputers and Parallel Processing

3.1 Introduction

The transputer has been designed as a processing element which can be connected together in a simple way to provide a computing capability far in excess of that attainable by any single processor-based approach whether a microprocessor or a large supercomputer. Unlike many previous processor designs such as the INTEL 8086 or 80286 which were developed as general purpose computing devices, the emergence of the transputer and its programming language Occam have gone along hand in hand. In fact specific features in the architecture of the transputer were specifically designed for Occam in order to provide high performance. Parallel processing can be defined as a technique for increasing the computational speed of a task by dividing it into several sub-tasks and allocating several processors to execute multiple sub-tasks concurrently.

The first part of the chapter deals with concurrency issues and describes the architecture of the transputer. The second part of the chapter will deal with the Occam programming language that allows applications to be described as a collection of processes which operate concurrently and communicate via channels. Finally it will be shown how the direct mapping of Occam processes for real-time control applications onto an array of transputers is possible.

3.2 Parallel Programming

Computational parallelism can be used to solve specific problems within specific application areas. Jones [1988] has identified three areas of 'parallelism' that represent the maximum speed-up of an problem using multiple computing elements.

Theoretical Parallelism. - To improve performance almost linearly with the increase of processing elements. This theoretical speed-up very rarely occurs because of reasons stated in the next two points.

Natural Parallelism. - A proportion of the processor's work-load must be executed sequentially. This would be the ideal case but as shown in the next point, it can not always be applied.

Applied Parallelism. - Since the particular structure of the parallel processing elements may not exactly match the 'natural' parallelism, (e.g.. a 2-D array of processors attempting to solve a 3-D problem), a further reduction in processor utilisation will occur.

The designer of parallel processing systems has three main choices:

i) Optimise the architecture for a particular problem, with an inherent large degree of parallelism to match, and hence track the 100% processing element 'theoretical' curve.

ii) Use a few very powerful processors utilising each processing element to its maximum efficiency.

iii) Use many small and cheap processors to increase the number of processing elements cost-effectively.

The transputer falls into the area discussed in (ii).

3.3 The Transputer

The transputer was first introduced by INMOS in September 1985. The first member of the family was the IMS T414 32-bit device. Since its launch concurrency has been applied in a wide variety of applications such as simulation, robot control, image synthesis, and digital signal processing.

The transputer is a microcomputer with its own local memory and with four links for connecting one transputer to other transputers. In the transputer product range each device contains special hardware for tailoring it for special use. For example a peripheral controller such as a hard disc controller has interfaces tailored to the requirements of a specific device.

A transputer can be used in a single processor system or in a network to build high performance concurrent systems.

The chip architecture simplifies system design by using point to point communication links. Every member of the transputer family has one or more standard links, each of which can be connected to a link of some other component. This allows networks of arbitrary size and topology to be constructed.

- Point to point communication links have many advantages over multi-processor buses:
- There is no contention mechanism, regardless of the number of transputers in the system, i.e.. data does not have to share a processor bus.
- There is no capacitive load penalty as transputers are added to the system.

The communication bandwidth does not saturate as the size of the network increases. The larger the number of transputers in the system the higher the total communication bandwidth of the system.

Transputer systems can be designed and programmed using many high level languages such as C, Pascal, Fortran. However the programming language Occam, which allows an application to be described as a collection of processes which operate concurrently and communicate through channels, was considered to be superior. The transputer can therefore be used as a building block for concurrent processing systems, with Occam as the associated design formalism.

Many computation intensive applications can exploit large arrays of transputers, the system performance depending on the number of transputers, the speed of inter processor communication and the performance of each transputer processor.

Many important applications of transputers involve floating point arithmetic. The IMS T800, can increase performance of such systems by offering greatly improved floating point and communication performance. The IMS T800-30, introduced in the middle of

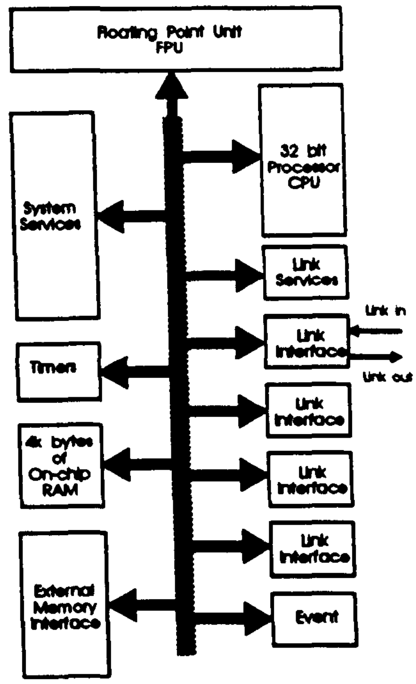

Figure 3.1 - Transputer architecture (IMS T800)

1988 is capable of sustaining over two and a quarter million floating point operations per second. The comparative figure for the IMS T414 transputer is somewhat less than one thousand floating point operations per second.

3.4 Transputer Family

The Inmos IMS T414 has a 32 bit processor, 2 Kbytes of fast memory on chip, a 32 bit external memory interface and 4 links for connection to other transputers. The currently fastest available version of this product, the IMS T414-25, has a 40 ns internal cycle time, and achieves about 12.5 million instructions per second (MIPS) on sequential programs.

The second transputer to become available was the IMS T212. This device is very similar to the T414 but has a 16 bit integer processor and a 16 bit external memory interface. The T212 has a sister, the IMS M212 disc processor. This contains a 16 bit processor, RAM, ROM, 2 inter transputer links and special hardware to control both winchester and floppy discs.

The current flagship of the transputer family is the T800 transputer, see figure 3.1. Architecturally it is very similar to the T414 but includes a floating point processor as standard.

3.5 Transputer Physical Architecture

Internally the IMS T414 consists of memory, processor and communication system connected via a 32 bit bus. The bus also connects to the external memory interface enabling additional local memory to be used. The T800 with its on-chip floating point processor is only 20% larger in area than the T414. The small size and high performance come from a design which takes careful note of silicon economics.

☐ Central Processing Unit (CPU)

The CPU contains three registers A,B and C. They are used for integer and address arithmetic and effectively form a hardware stack. Loading a value into the stack pushes B into C, and A into B before loading A. Storing a value from A pops B into A, and C into B. The processor has a microcoded scheduler which enables any number of concurrent processes to be executed together, sharing the processor time. This removes the need for a software kernel. The scheduler works in such a way that inactive processes do not consume any processor time. It allocates a portion of the processor time to each process in turn. Each process runs until it has completed its action, but is taken off the processor queue whilst waiting for communication from another process or processor, or for a time delay to complete. In practice process switch times are less than 1 microsecond.

☐ Process priority

The transputer supports two levels of priority. Priority 1 (low priority) processes are executed whenever there are no active priority 0 (high priority) processes. High priority processes are expected to execute only for a short time period. If one or more high priority processes are able to proceed, then one is selected and runs until it has to wait for communication, a tifmer input, or until it completes processing. Active processes waiting to be executed are held in two lists of process work spaces, one for high priority processes and the other for low priority processes. Each list is implemented using two registers, one of which points to the first process in the list, the other to the last.

It will be seen later how these two levels of priority are used in real-time control applications.

☐ Communications

Communication between processes is achieved by means of channels. Process communication is point to point, synchronised and unbuffered. As a result a channel needs no process queue, no message queue and no message buffer.

A channel between two processes executing on the same transputer is implemented by a single word in memory. A channel between processes executing on different transputers is implemented by point to point links.

☐ Timers

The transputer has two 32-bit timer clocks. One timer is only accessible to high priority processes and is incremented every microsecond. The other is accessible only to low priority processes and is incremented every 64 microseconds.

☐ The Floating Point Unit (FPU)

The 64 bit FPU provides single and double length arithmetic. It is able to perform floating point arithmetic concurrently with the central processor unit sustaining in excess of 2.25 Mflops on a 30 MHz device. All data communication between memory and the FPU occurs under the control of the CPU.

☐ Links

There are up to four identical bi-directional serial links which provide synchronised communication between processors and with the outside world. Each link comprises an input channel and an output channel. A link is implemented by connecting a link interface on one processor to a link interface on an other processor.

The links support the standard communication speed of 10 Mbits per second. In addition they can be used at 5 or 20 Mbits per second.

3.5.1 I/O Interfacing

Two methods of interfacing are available with the transputer [INMOS 1987], allowing real-time control systems to be implemented.

Memory Interface - Using the memory interface fast I/O is possible, four bytes transferred per three processor cycles, provided zero wait-state memory is used. The speed is not a continuous speed because the memory interface is also used for instruction fetching. Communication with I/O is asynchronous.

Link Adapter - The use of the transputer's serial links for communication results in a slower peak speed for I/O transfers than with the memory interface. The link speed of 20 Mbits/sec results in a one way communication of 1.74 MBytes/s. This communication rate can be sustained through continuous transfer made by the link control unit. Four bytes can be transferred in about 2 microseconds.

The use of the serial link for I/O has the advantage that it fits into the Occam programming model. Communication with I/O is synchronous.

3.6 Occam

Occam is the programming language for the transputer. Occam can be thought of as the assembly language for the transputer because there is a direct relationship between Occam processes and processors. Occam is the first language to be based upon the concept of parallel, in addition to sequential, execution, and to provide automatic communication and synchronisation between concurrent processes.

Occam provides the necessary framework for designing concurrent systems using transputers. The design task is eased because of the architectural relationship between Occam and the transputer. A program running on a transputer is formally equivalent to an Occam process, so that a network of transputers can be described as an Occam program.

In Occam programming parts of a program are referred to as processes. A process starts, performs a number of actions, and then finishes. This definition fits an ordinary sequential program, but in Occam more than one process may be executing at the same time, and

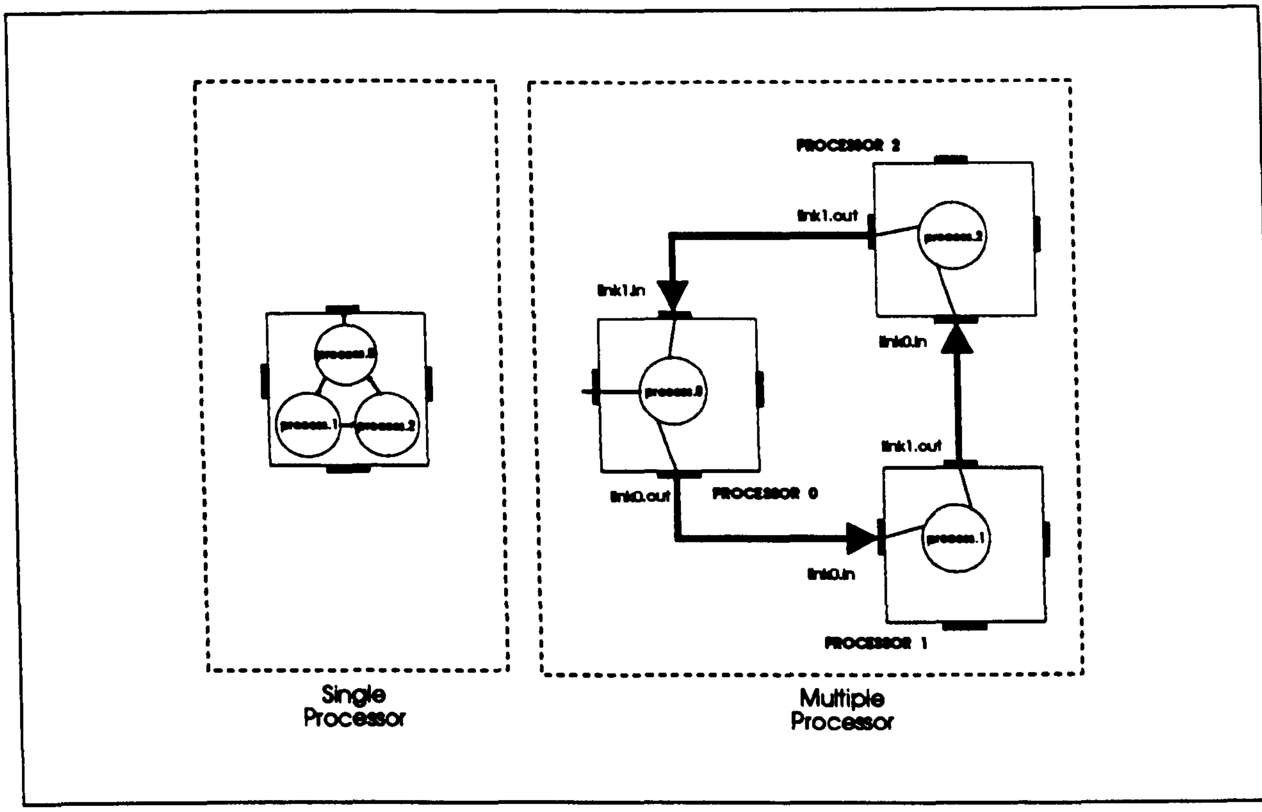

Figure 3.2 - Occam program development

processes can send messages to another process, across a channel. The channel behaves like a pipe joining the two processes.

A channel is a one way point to point link from one process to another. A channel can pass values either between two processes running on the same processor or between two processes running on different processors. In the first case the channel would be a location in memory, rather like the fixed storage location of a global variable. In the second case the channel could represent a real hardware link, such as a transputer link or other serial communication line. Both cases are represented identically in an Occam program.

An Occam channel describes communication in the abstract, and does not depend on the physical implementation. Thus programs can be written using channels without having to worry about exactly where the different processes will be executed. Internally, each process can be designed as a set of communicating processes. The system design is therefore hierarchically structured. At any level of design the program is only concerned with a small and manageable set of processes. The Occam language is independent of hardware.

A program can be developed on a single processor. When it is finished and proven the processes in the program may be distributed onto different processors by making a few simple declarations at the beginning of the program, see figure 3.2 .

An entire system can be designed and programmed in Occam, from system configuration down to low level I/O and real time interrupts.

The Occam programming language is fully described in many text books, [Pountain et al. 1988,Graham et al. 1990,Inmos 1988], but a brief description of the fundamentals will be given in the next section.

3.6.1 Fundamentals of Occam programming

Occam primitives - All Occam programs are built from three types of primitive processes,

```
x := y   -- assign variable x to expression y[1]
link1.in ? x   -- input variable x from channel chan.1
link0.out ! y   -- output expression y to channel chan.2
```

These primitive processes are combined to form constructs,

☐ **SEQ construct**

SEQ merely says evaluate the following processes in sequence. A SEQ process works like a program in any conventional programming language. SEQ is compulsory in Occam where two or more processes are to run in sequence. An example showing a simple buffer process and using the primitive processes is shown below. The indentation is used to indicate program structure.

1 -- Occam comment

```
BYTE char:
SEQ
    keyboard ? x -- Input data from channel 'keyboard' into x
    screen ! x -- output x on channel 'screen'
```

☐ PAR construct

The PAR construct means execute the following processes in parallel. The components of a parallel construct may not use shared variables, they must communicate only through channels. An example of this below, uses two concurrent versions of the previous example, joined by a channel to form a double buffer.

```
PAR
    BYTE x:
    SEQ
        keyboard ? x -- process 1
        channel.1 ! x
    BYTE x:
    SEQ
        channel.1 ? x -- process 2
        screen ! x
```

The **PAR** process terminates when all its component processes have terminated. Note that parallel processes cannot share variables, consequently the variable named '**x**' refers to two physically independent local variables.

In **Occam,** variables are used for storing values, while channels are used for communicating values.

☐ PRIoritized PAR

The component processes in a **PRI PAR** are assigned a priority according to the textual order in which they appear in the program. The first has highest priority. This construct finds use in may real-time applications where it is important to interrupt a low priority process. The example below shows an event handler. This process is run at high priority and can interrupt a low priority process.

```
PRI PAR
   INT x:
   SEQ
      alarm ? x -- high priority process
      ... take action on alarm[2]
   REAL32 y:
   SEQ
      data.channel ? y -- low priority process
      .. normal process
```

☐ SKIP and STOP Processes

Occam supports two special processes **STOP** and **SKIP**. **SKIP** may be thought of as a process which does nothing. **SKIP** may be used in a partly completed program in place of a process which will be written later, but for the moment can be allowed to do nothing. For example a process which is to drive an electric motor could be replaced by SKIP when testing the program without a motor.

STOP may be thought of as representing a process which doesn't work or is broken. It can be used when building a program consisting of a number of parallel processes as part of one process to halt the process whilst debugging the other process.

A stopped process never continues.

```
INT flag:
SEQ
   channel.input ? flag
   IF
      flag = -1
         STOP
   TRUE
      SKIP
```

This process will monitor the input channel for a flag value of -1, say an error. If an error condition occurs, the conditional IF process will execute the process STOP, which will cause the process to lock at this point, and proceed no further.

2 ... code descriptor

☐ ALTernative Process

The **ALT** process is an unfamiliar construct in conventional programming languages. The ALT process acts like a multiplexer. It watches a number of input processes and executes the process associated with the first input to be ready. In the example shown below, if chan2 were the first to produce an input, then only the second process would execute.

```
CHAN OF INT chan1,chan2,chan3:
INT x:
SEQ
  ALT
    chan1 ? x
      ... process 1
    chan2 ? x
      ... process 2
    chan3 ? x
      ... process 3
  ... main process
```

☐ PRIoritised ALTernative

Similar to the **PRI ALT** construct **PRI ALT** assigns component processes to certain priorities. In a **PRI ALT**, when two inputs become ready simultaneously, the component process with the highest priority will be executed first.

```
INT time:
SEQ
  PRI ALT
    sample ? time -- always do this first if ready
      SKIP
    TRUE&SKIP -- else
      ... main process
```

☐ Replicated Processes

One of the most powerful features of Occam is that it allows the construction of arrays of processes in addition to data and channel arrays.

Replicated **SEQ,PAR** and **ALT** processes can be created. Individual processes in a replicated construct can be referred to using the replicator index.

☐ Replicated SEQ

The construct of the replicated SEQ is as follows:

```
SEQ index = 0 FOR 5
  input.channel ? data.array[index]
```

☐ **Replicated ALT**

The replicated ALT consists of a number of identically structured alternatives each of which is triggered by input from a channel.

Like the replicated PAR, it is an immensely powerful and significant construct. An example of a replicated ALT is as follows:

```
ALT index = 0 FOR 10
  input.channel[index] ? data
    output.channel ! data
```

The process segment acts as a multiplexer, merging the communication from 10 channels down onto a single channel.

Replicated ALT constructs provide an elegant and concise way to build and control switching networks of all types.

3.6.2 Real-time support and I/O handling.

When implementing real-time control systems where the digital controller is connected to a wide variety of devices for monitoring sensors and controlling actuators the response time to external events is crucial. These devices communicate information to and from the controller via some type of i/o registers. Event signals can be generated to indicate to the controller to perform a certain task or to indicate a fault condition.

3.6.2.1 Occam timer support

The on-chip hardware timer supported by the transputer is considered as a process. This has allowed the real-time interfaces to be developed in data flow description following the Occam model of programming. Because the Occam timer is considered as a process, it can be read by an input statement via a specially declared timer channel. A single timer process may be read by several concurrent processes.

```
TIMER clock:
INT time:
SEQ
  ...
  clock ? time  -- read value of timer 'clock' into 'time'
  ...
```

The value read from the timer process is of integer type, the value derived from a clock which increments at regular intervals. The value of this clock is cyclic, when the clock has reached its most positive value the next increment results in the most negative value.

3.6.2.2 Delayed input

One of the set of modulo operators that is supported by Occam is the operator **AFTER**. This allows a timer to be read until a specified time value has been reached. An example of this is shown below where the next process will not be executed until the value of the clock is later than the value of time.

```
TIMER clock:
SEQ
  ...
  clock ? AFTER time
  ...
```

3.6.2.3 Measuring time intervals

The most common use of time interval measurement is for benchmarking processes. The example below shows a typical application of this type of timer structure. The time value measured in these applications is the elapsed time and not the processor time used by the process. If many processes are running concurrently on a single processor the resulting benchmark may be incorrect due to the fact that each concurrent process is being timesliced each getting a share of the cpu time.

```
TIMER clock:
INT time1,time2,time:
SEQ
   clock ? time1  -- read start time into time1
.  .. run benchmark
   clock ? time2  -- read end time into time2
   time := time2 MINUS time1  -- calculate elapsed time
```

3.6.2.4 Generating delays

The Occam timer construct can be used readily to generate events at regular intervals by implementing a delay process. The examples below shows this construct which implements the delayed input construct **AFTER.**

```
TIMER clock:
INT time.now:
VAL delay is 500: -- delay time in clock 'ticks'
SEQ
clock ? time.now
clock ? AFTER time.now PLUS delay
```

3.6.2.5 Interrupts

Interrupt handling is the most commonly used method to inform the transputer that an event has happened or that an action is required. The structure of a interrupt handling application is shown below. Making the interrupt handling process high priority and the rest of the processes low priority, enables the high priority process to become scheduled quickly after it becomes ready with a typical response time of 19 processor cycles.

```
PRI PAR
   ... interrupt handling process
   PAR
      ... low priority process 1
      ... low priority process 2
      ... low priority process 3
```

Summary

This chapter has given an brief overview of parallel processing and its implementation using the transputer as the processing element. The transputer has been shown to be a medium sized processing element which has high computational power at relatively low cost. The flexibility of the transputer is only limited by the number of serial communication links.

Using the programming language Occam it is possible to develop small procedures of code called processes that can be tested individually then linked to other processes via communication links. On one processing element (processor) these links are described in software. On multiple processors these links can be a combination of hardware and software communication paths. It has been shown that the applications can be described as a collection of processes tested on a single transputer then distributed among many processing elements to achieve the desired computational speed up.

Real-time support on the transputer is in the form of two on-board timers that allow the development of interrupt, delay and sampling processes. The use of these has been shown in some simple examples.

The next chapter involves the development and simulation of control algorithms. These control algorithms will be implemented on the transputer by allocating different parts of the control algorithm to different processors thus reducing computational time and hence increasing sampling rates. Handling of data input and output will be discussed in chapter 5.

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Chapter 4

System Simulation and Controller Design

4.1 Introduction

The design of a suitable controller cannot be undertaken without a suitable description of the plant. This description as previously discussed can take the form of either Laplace transfer functions or state space representations. In order to arrive at these descriptions the basic structure and dynamics of the plant have to be understood. One method of modelling systems is to derive the plant equations of motion. Another method is to obtain the transfer function of the system directly by experimental testing.

Once a plant model has been formulated a controller can be designed using one of the methods previously mentioned, simulation can then be used to test the combined plant and controller.

The use of simulation to model a physical system has several benefits as a design tool:

- It enables the system designer to gain a better understanding of the system and its constituent components
- Fast evaluation of many varying control strategies without resorting to actual testing.
- Ability to modify the variables of the physical system along with the facility to introduce load disturbances and noise.
- Analysis of experimental data for system identification of unknown plants.

Two simulation and control design packages have been used during this study.

The first, ACSL, is a simulation language designed for modelling and evaluating the performance of continuous and discrete systems that can be described by time-dependent, non-linear differential equations or transfer functions.

The second, Ctrl-C, is an interactive language for linear system analysis and design. It provides a work-bench for system simulation, signal processing, matrix analysis, and graphics.

The use of a software interface between the two systems has allowed the design of a control system to proceed as follows:

- Linearisation of non-linear plant model from ACSL to Ctrl-C.
- Representation of linear model in Ctrl-C in state space form.
- Design of control system in Ctrl-C.
- Testing of control design on ACSL model from within Ctrl-C (via interface).
- Comparison of results between linear model (Ctrl-C) and non-linear model (ACSL)
- Robustness analysis.

The communication of information between these two design and simulation packages can be seen in figure 1.0.

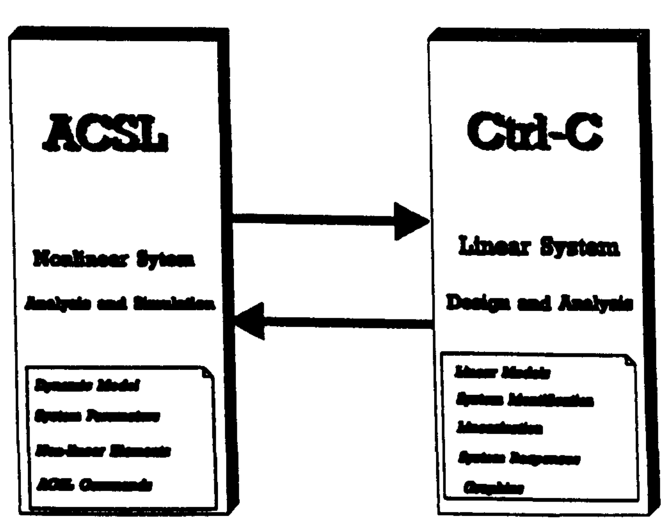

Figure 4.1 - CASD Interaction

4.2 System Modelling

The positive and negative film are driven by two independent capstan drive systems. The capstan drive consists of two motors directly coupled, (via flexible couplings), to drive roller assemblies, see chapter 5. Each motor has its own servo amplifier system allowing separate control of each drive element.

4.2.1 Equations of motion

☐ DC Servomotor - The servo motors used in the capstan drive system can be described by the following dynamic equations:

$$J_1 \frac{d\,\omega_1}{d\,t} = K_{t1}\, i_1 - K_{d1}\, \omega_1 - r_1\, T - \tau_{f1} \tag{4.1}$$

$$J_2 \frac{d\,\omega_2}{d\,t} = K_{t2}\, i_2 - K_{d2}\, \omega_2 - r_2\, T - \tau_{f2} \tag{4.2}$$

$$L_1 \frac{d\, i_1}{d\,t} = e_1 - R_1\, i_1 - K_{b1}\, \omega_1 \tag{4.3}$$

$$L_2 \frac{d\, i_2}{d\,t} = e_2 - R_2\, i_2 - K_{b2}\, \omega_2 \tag{4.4}$$

Figure 4.2 shows the motor equations in block diagram form.

☐ Film tension - The only physical link between the two film drives is the film itself. The dynamics of the film can de described by,

$$\frac{d\,T}{d\,t} = K\,(\omega_2\, r_2 + \omega_1\, r_1) + C\,(\dot{\omega}_2\, r_2 + \dot{\omega}_1\, r_1) \tag{4.5}$$

where the system state variables are,

$i_{1,2}$ = Motor currents

$\omega_{1,2}$ = Motor angular velocity

T = Film tension

$e_{1,1}$ = Motor control signal

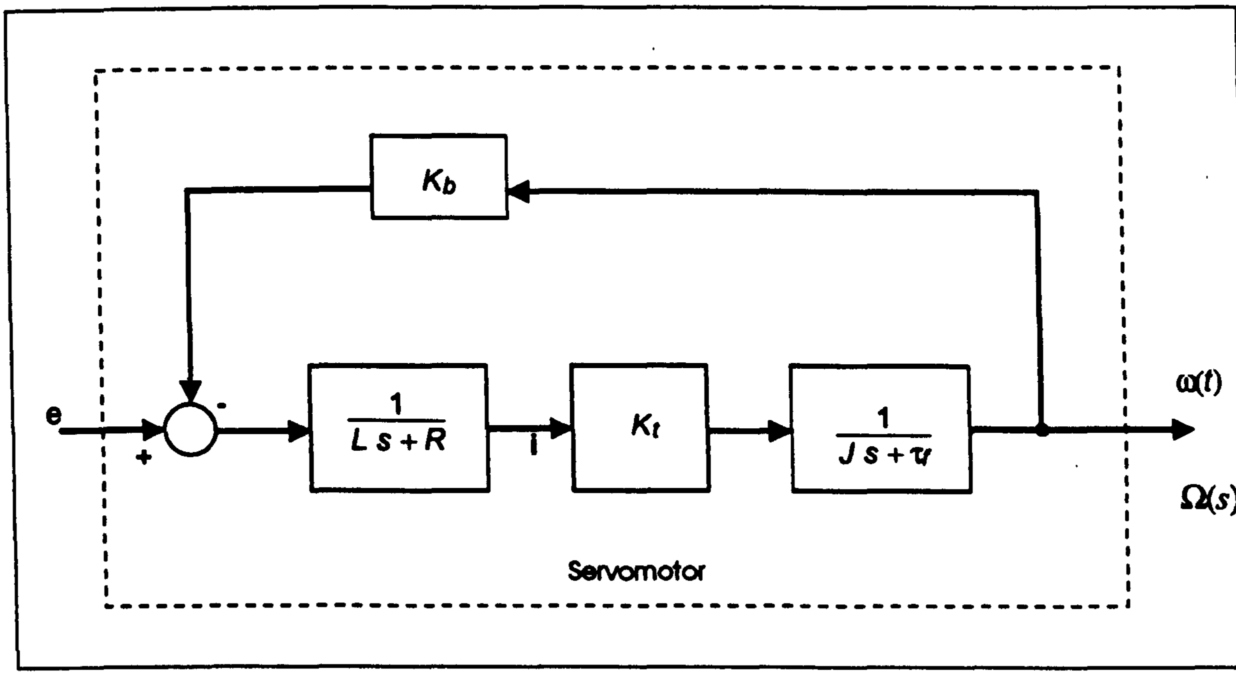

Figure 4.2 - Block description of servomotor

- ☐ Amplifier - The drive source for the servomotor is a current amplifier. This type of amplifier gives a constant output current for a given input voltage. The amplifier system can be considered as operating in torque mode and can be described by the Laplace transform as,

$$\frac{i_{out}(s)}{v_{in}(s)} = \frac{K_{amp}}{1 + \tau_{amp} s} \tag{4.6}$$

where K_{amp} is the gain of the amplifier and $\frac{1}{\tau_{amp}}$ is the bandwidth of the amplifier in torque configuration.

Examination of the dynamic equations of the servomotor show that the terms associated with the electrical behaviour of the motor, (4.3) and (4.4), do not influence the current actually being delivered to the motor. The overall transfer function describing the motor driven by a current amplifier is given by (4.7). The block diagram representation of this system is shown figure 4.3.

$$\frac{v_{in}(s)}{\Omega(s)} = \frac{K_t \, K_{amp}}{(J\,s + \tau_f)\,(1 + \tau_{amp} s)} \tag{4.7}$$

The other plant parameters are shown below in Table 4.1.

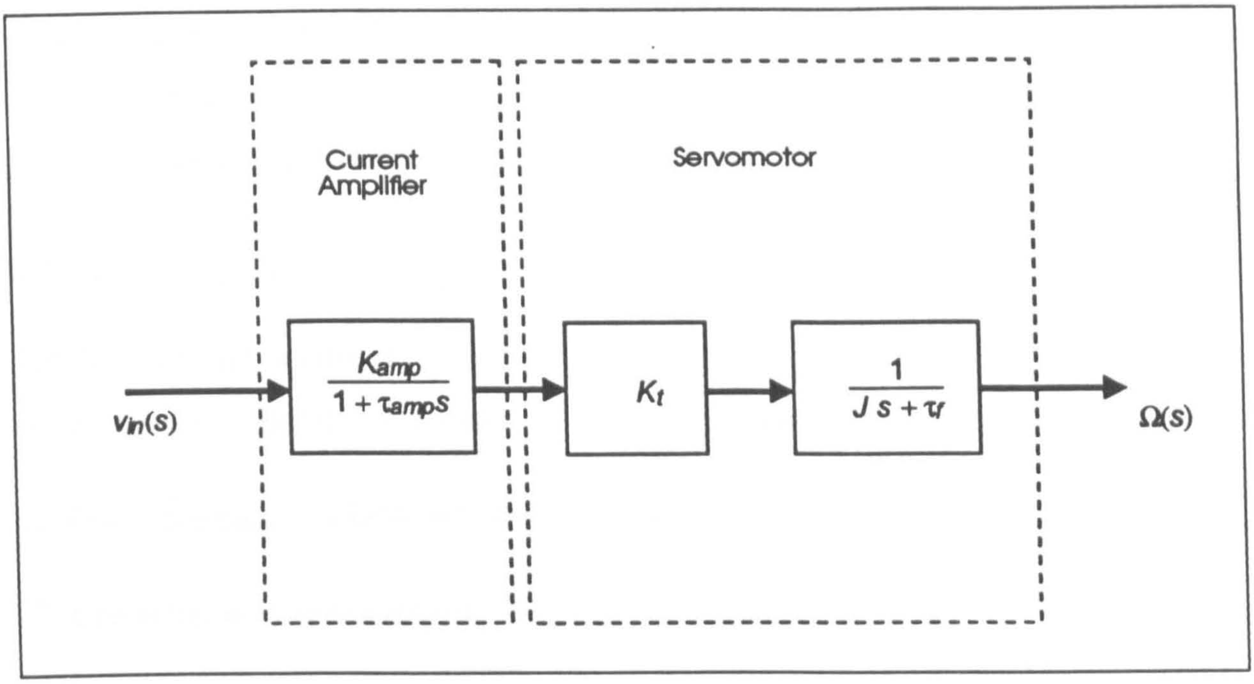

Figure 4.3 - Servomotor driven by current amplifier

The above dynamic equations describing the various elements of the capstan drive system were used to build a simulation model in ACSL. The model description also included non-linear elements of the system such as amplifier saturation limits, start up friction (stiction), and tension limits e.g. tension in the film can only be positive.

Properties of film such as damping and stiffness vary from manufacturer to manufacturer. The two main materials used for the manufacture of film, polyester and acetate also have

Parameter	Description	Value	Units	Notes
$J_{1,2}$	Capstan hub inertia	2.61E-06	Kg m^2	
$K_{t\,1,2}$	Motor torque constant	0.074	N m	± 10%
$K_{d\,1,2}$	Motor damping constant	1.35E-06	N m/$rads^{-1}$	
$r_{1,2}$	Capstan hub radius	0.0125	m	
$\tau_{f1,2}$	Torque friction	0.0056	N	
$L_{1,2}$	Motor inductance	0.0017	H	
$R_{1,2}$	Motor resistance	2.15	Ohms	@ 25°C
$K_{b\,1,2}$	Back EMF constant	0.075	V/$rads^{-1}$	± 10%
K	Film stiffness	20,000	N m	Agfa (Neg.)
C	Film damping coefficient	14.0	N m s	Agfa (Neg.)

Table 4.1 - Physical Plant Parameters

differing characteristics. Appendix B describes fully the testing procedures used to determine the physical properties for various makes of film. The results show clearly the variable characteristics of film used in the motion picture industry.

4.3 Controller Design

The design of the capstan servo is based on the optimal method of control system design as discussed in Chapter 2. It consists of three main stages,

- ☐ Controller based on feedback of all the states.
- ☐ Controller with added integral control.
- ☐ Controller with added integral control and estimator.

The ACSL simulation model using the equations of motion as described above was linearised to give a set of state-space equations. Using Ctrl-C, design by the various control strategies listed above could be derived using the linear model description. The resulting control algorithms were then incorporated into the ACSL model which was run under different operating conditions to examine the effect of the controller on external disturbances and how this affected the desired output of the system i.e. film tension and speed response. The final test of these controllers was made on the laboratory test rig. These results are shown in later chapters.

4.3.1 System specification

The capstan drive system can be described as a multi-input multi-output (MIMO) system. The inputs to the system are motor current control signals. The outputs of the system are surface film speed and film tension. For feedback, the speed and motor current are directly measured. The film tension can be estimated directly from these measurements.

The system specification is as follows:

i) Transient response to a step disturbance of speed to have a settling time of less than $\frac{\textit{film frame–width}}{\textit{command speed}}$, with negligible overshoot. Speed disturbances are typically in the order of 5% of film running speed.

Film Speed (m/s)	Settling Time to Step Disturbance (ms)	Closed Loop Bandwidth (ω_0) (rad/s)	
	Tension/Speed	Tension ($\zeta = 0.7$)	Speed ($\zeta = 1$)
1	19.5	337	236
2	9.5	690	483
3	6.3	1035	724
4	4.7	1380	966
5	3.8	1724	1207

Table 4.2 - Response specification

ii) Transient response to step disturbance of tension to have a settling time of $\frac{\textit{film frame–width}}{\textit{command speed}}$, with no more than 5% overshoot. Tension disturbances are typically in the order of 10% of running tension.

iii) Zero steady state error to constant speed and tension commands.

iv) Each drive motor is limited to 6A peak and 3A continuous current.

Typical film tension over the printing head is between 8 and 15N. Film printing speeds currently reach 3.5 m/s but the aim is to increase this to 5 m/s. The relationship between system response and frame rates is outlined in table 4.2 .

Specification (iii) must account for any model inaccuracies or constant disturbance inputs. If this specification is satisfied the controller design will exhibit good "robustness"[1].

4.3.2 Controller design formulation

From the equations of motion of the system derived in the previous section we can write the state-space equivalents,

---

1 Definition of a robust system - For a change in plant gain due to parameter changes then system will still have a zero steady state error to a constant input.

$$[\dot{\mathbf{x}}]=\begin{bmatrix} -2000 & 0 & 0 & 0 & 0 \\ 0 & -2000 & 0 & 0 & 0 \\ 3317 & 0 & -5 & 0 & -553 \\ 0 & 3317 & 0 & -5 & -553 \\ 1368 & 1368 & 831 & 831 & 456 \end{bmatrix}\mathbf{x}+\begin{bmatrix} 6000 & 0 \\ 0 & 6000 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\mathbf{u} \quad (4.8)$$

where the desired outputs are

$$\begin{bmatrix} T \\ V \end{bmatrix}=\begin{bmatrix} 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & -0.0063 & 0.0063 & 0 \end{bmatrix}\mathbf{x} \quad (4.9)$$

where

$$[\mathbf{x}]=\begin{bmatrix} i_1 \\ i_2 \\ \omega_1 \\ \omega_2 \\ T \end{bmatrix} \quad \text{and} \quad \mathbf{u}=\begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

Figure (4.4) shows the frequency response of the plant. The eigenvalues of the plant matrix in (4.8) are,

$$s=-5.0, -230 +/- 932j, -2000$$

The open loop resonance at 932 rad/s is from the combination of the film dynamics and the capstan/motor inertias. This system can be approximated to a second order mass-spring-damper system.

The approximation to a second order system allows the bandwidth of the system ω_b as indicated on the frequency response to be approximately related to the natural frequency of the system. From the specification the 5% overshoot on the tension response gives a damping factor ζ of 0.7. The specification for the speed calls for negligible overshoot, critically damped, giving a damping factor of 1.

To allow the specification on settling time to be reached, a sample frequency of 25 times faster than the maximum bandwidth was chosen.

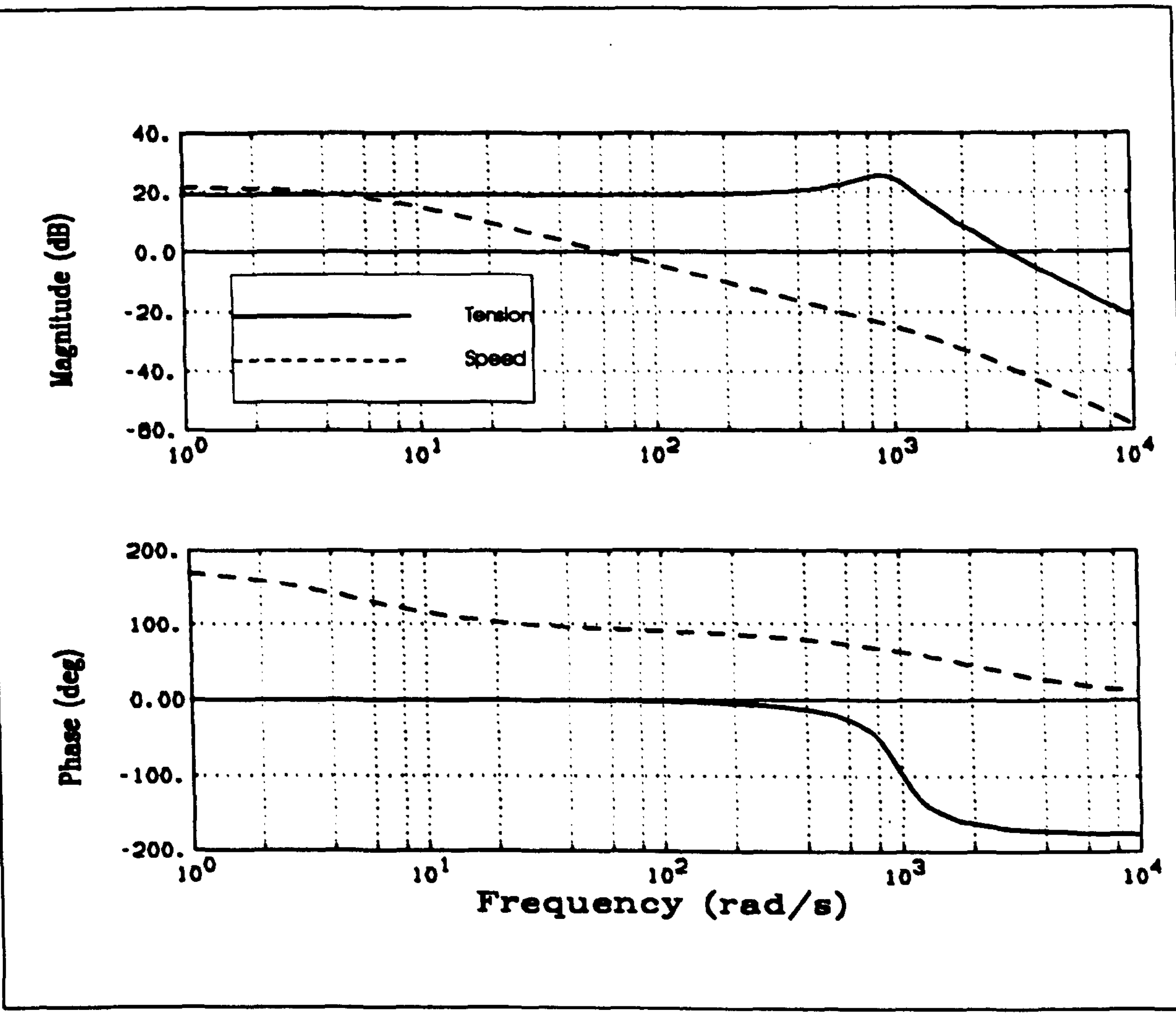

Figure 4.4 - Open loop frequency response of plant

4.3.3 Reference input structure LQR controller.

4.3.3.1 Full-state feedback

The first stage of the controller design is to assume all states are available for feedback even though the tension in the film cannot be directly measured and in practice is subject to much external disturbance. The design is based on the linear quadratic regulator design outlined in Chapter 2.

The output quantities to be controlled are the film speed V and film tension T. The weighting of these outputs can be defined in the cost $\underline{Q}_1$ as outlined in Section 2.

Although the specification states that there should be no steady-state error we will weight each element according to a very small deviation which as (4.10) indicates gives a weighted matrix showing the relative importance of these parameters. The cost $\underline{Q}_1$ is initially chosen as,

$$Q_1 = \begin{bmatrix} 10 & 0 \\ 0 & 500 \end{bmatrix} \tag{4.10}$$

and

$$Q_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{4.11}$$

the cost Q_2 indicates that each control input is to be used equally which is sensible as both drives are assumed identical and the system is to be used to print in both directions.

A sample time of 150 μs was chosen. The state-space matrices were discretized using this time interval giving,

$$\Phi = \begin{bmatrix} 0.7408 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.7408 & 0.0000 & 0.0000 & 0.0000 \\ 0.4214 & -0.0083 & 0.9942 & -0.0050 & -0.0798 \\ -0.0083 & 0.4214 & -0.0050 & 0.9942 & -0.0798 \\ 0.1979 & 0.1979 & 0.1201 & 0.1201 & 0.9240 \end{bmatrix} \tag{4.12}$$

$$\Gamma = \begin{bmatrix} 0.7775 & 0.0000 \\ 0.0000 & 0.7775 \\ 0.2005 & -0.0025 \\ -0.0025 & 0.2005 \\ 0.0902 & 0.0902 \end{bmatrix} \tag{4.13}$$

Using the cost quantities above, a discrete equivalent of the LQR feedback gains could be formed,

$$\mathbf{K} = \begin{bmatrix} 0.6073 & 0.3809 & 0.3876 & 0.2110 & 1.0178 \\ 0.3809 & 0.6073 & 0.2110 & 0.3876 & 1.0178 \end{bmatrix} \tag{4.14}$$

Using the reference state structure as discussed in section (2.) a state command matrix N_x can be formed from the plant's physical relationships at the desired command values,

$$\mathbf{N_x} = \begin{bmatrix} 0.1667 & -0.1210 \\ 0.1667 & 0.1210 \\ 0.0000 & -80.000 \\ 0.0000 & 80.000 \\ 1.0000 & 0.0000 \end{bmatrix} \tag{4.15}$$

Using these newly formed command and feedback gains the closed loop plant matrices can be formed as,

$$\Phi_{cl} = \Phi - \Gamma \times K, \text{ and}$$

$$\Gamma_{cl} = \Gamma \times K \times N_x,$$

giving,

$$\Phi_{c1} = \begin{bmatrix} 0.2686 & -0.2962 & -0.3014 & -0.1641 & -0.7914 \\ -0.2962 & 0.2686 & -0.1641 & -0.3014 & -0.7964 \\ 0.3006 & -0.0832 & 0.9170 & -0.0464 & -0.2814 \\ -0.0832 & 0.3006 & -0.0464 & 0.9170 & -0.2814 \\ 0.1088 & 0.1088 & 0.0661 & 0.0661 & 0.7404 \end{bmatrix} \quad (4.16)$$

$$\Gamma_{c1} = \begin{bmatrix} 0.9194 & -11.0077 \\ 0.9194 & -11.0077 \\ 0.2342 & -2.8745 \\ 0.2342 & 2.8745 \\ 0.2133 & 0.0000 \end{bmatrix} \quad (4.17).$$

Figure 4.5 and 4.6 show the step response of this full-state feedback system. The input is a unit step for both speed and tension commands. These results show that the tension has a settling time of approximately 0.001 sec. with an overshoot of less than 5%. The response to a unit step in speed meets the specification. Control effort for tension and speed are both within acceptable limits. The resulting gain matrix (4.14) has allowed the system to become well decoupled. This can be clearly seen from the step responses on each input. The control effort, discussed earlier, is directly proportional to the current signal, which shows that the speed of the film is directly proportional to the difference in current signal while the tension in the film is directly proportional to the sum of the current signal.

Figure 4.7 shows the effect of a constant disturbance of tension on the capstan system. This disturbance is typical of the tension associated with the external winding system which although buffered does have some effect on the printing head drive system. The next section uses the same full-state feed-back but with added integral control on the tension input to eliminate any steady-state error.

Full-state feedback with no external disturbance.

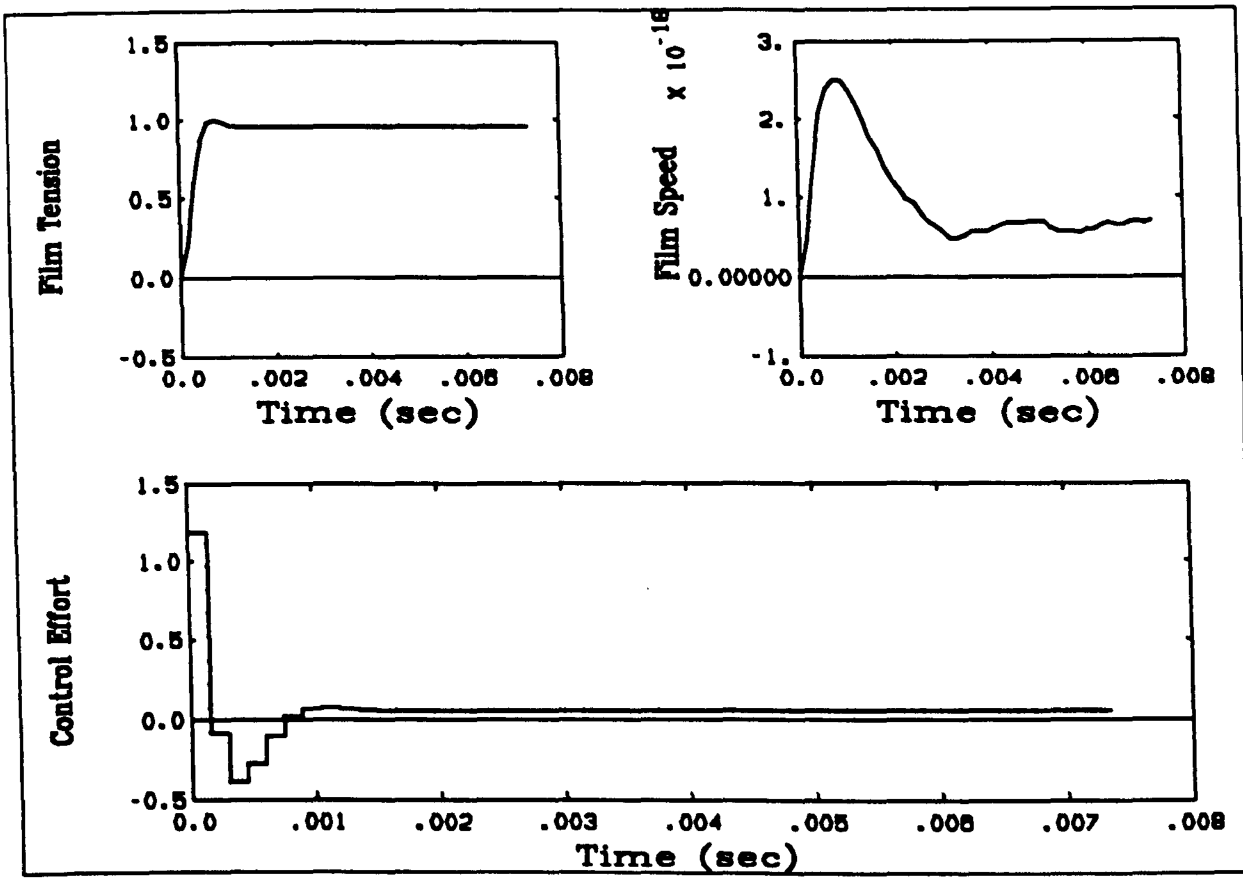

Figure 4.5 - Response of unit step tension input

Full-state feedback with no external disturbance.

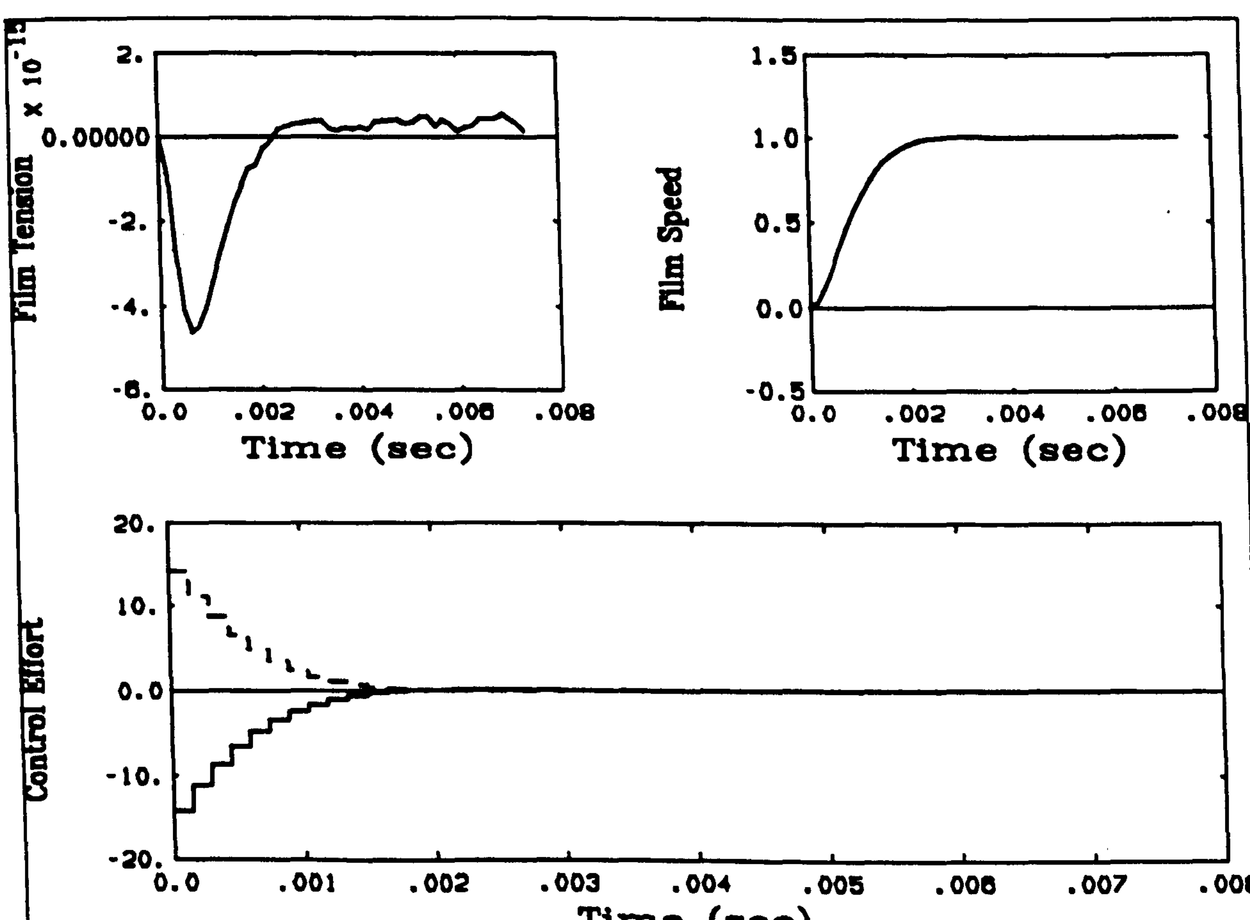

Figure 4.6 - Response of unit step speed input

Full-state feedback with constant external disturbance of 1N

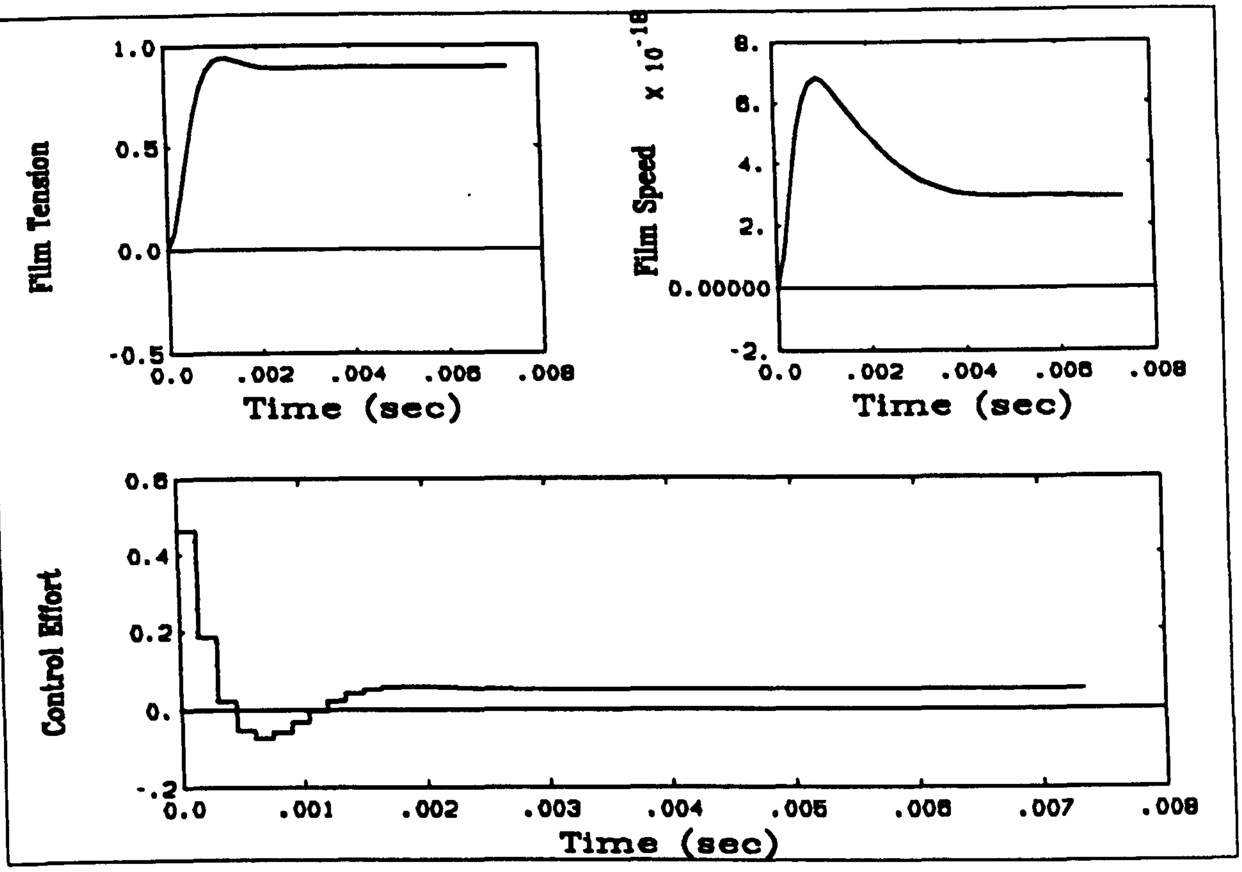

Figure 4.7 - Response of step input on tension

Full-state feedback controller.

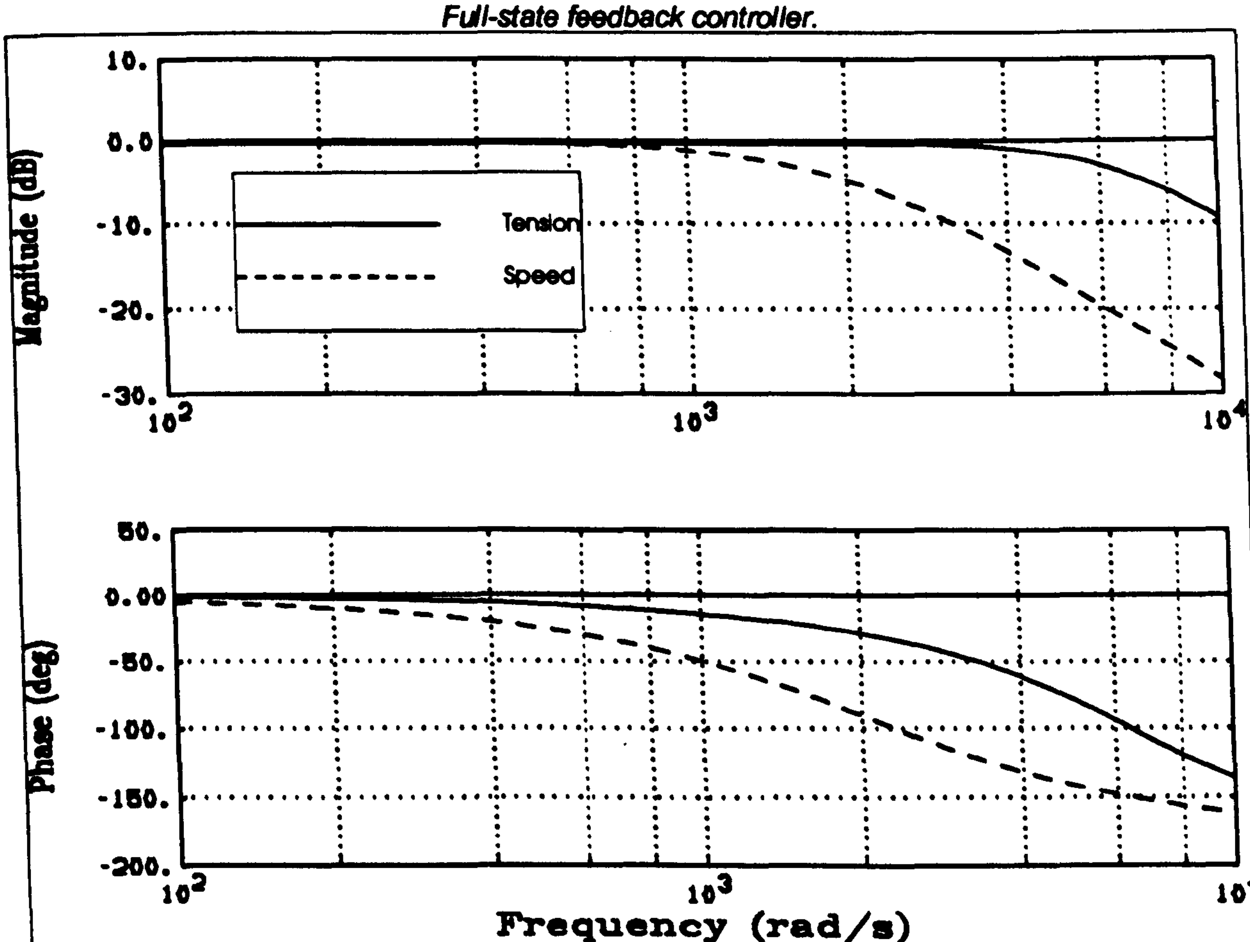

Figure 4.8 - Closed loop frequency response.

The closed loop frequency response (figure 4.8) for this full-state feedback controller shows that the specification has been achieved with a bandwith of 6000 rad/s for the tension and 1556 rad/s for the speed. The tension specification is higher than required. This specification can be reduced by reducing the tension weighting term. This will also have the effect of reducing the steady state error.

4.3.4 Full-state feedback with added integral control

In the next stage the aim is to reduce the steady state error on the tension value, and also to maintain the robustness of the system. The tension will be fed-back and the resulting tension error integrated. The resulting new system description is based on the augmented plant model represented by (2.29). This added state, (integral tension), is used to form new augmented state matrices. This has been readily accomplished by adding a third output consisting of the extra state giving the new output matrix,

$$H = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -0.0063 & 0.0063 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}. \tag{4.18}$$

The new discretized state matrices can be formed from (2.29) as,

$$\Phi_a = \begin{bmatrix} 1.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.7408 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & 0.7408 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.4214 & -0.0083 & 0.9942 & -0.0050 & -0.0798 \\ 0.0000 & -0.0083 & 0.4214 & -0.0050 & 0.9942 & -0.0798 \\ 0.0000 & 0.1979 & 0.1979 & 0.1201 & 0.1201 & 0.9240 \end{bmatrix} \tag{4.19}$$

$$\Gamma_a = \begin{bmatrix} 0.0000 & 0.0000 \\ 0.7775 & 0.0000 \\ 0.0000 & 0.7775 \\ 0.2005 & -0.0025 \\ -0.0025 & 0.2005 \\ 0.0902 & 0.0902 \end{bmatrix} \tag{4.20}$$

A new weighting matrix is also formed that weights the new state. This is given by,

$$Q_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 500 & 0 \\ 0 & 0 & 0.01 \end{bmatrix} \tag{4.21}$$

Full-state feedback with added integral control - no external disturbances.

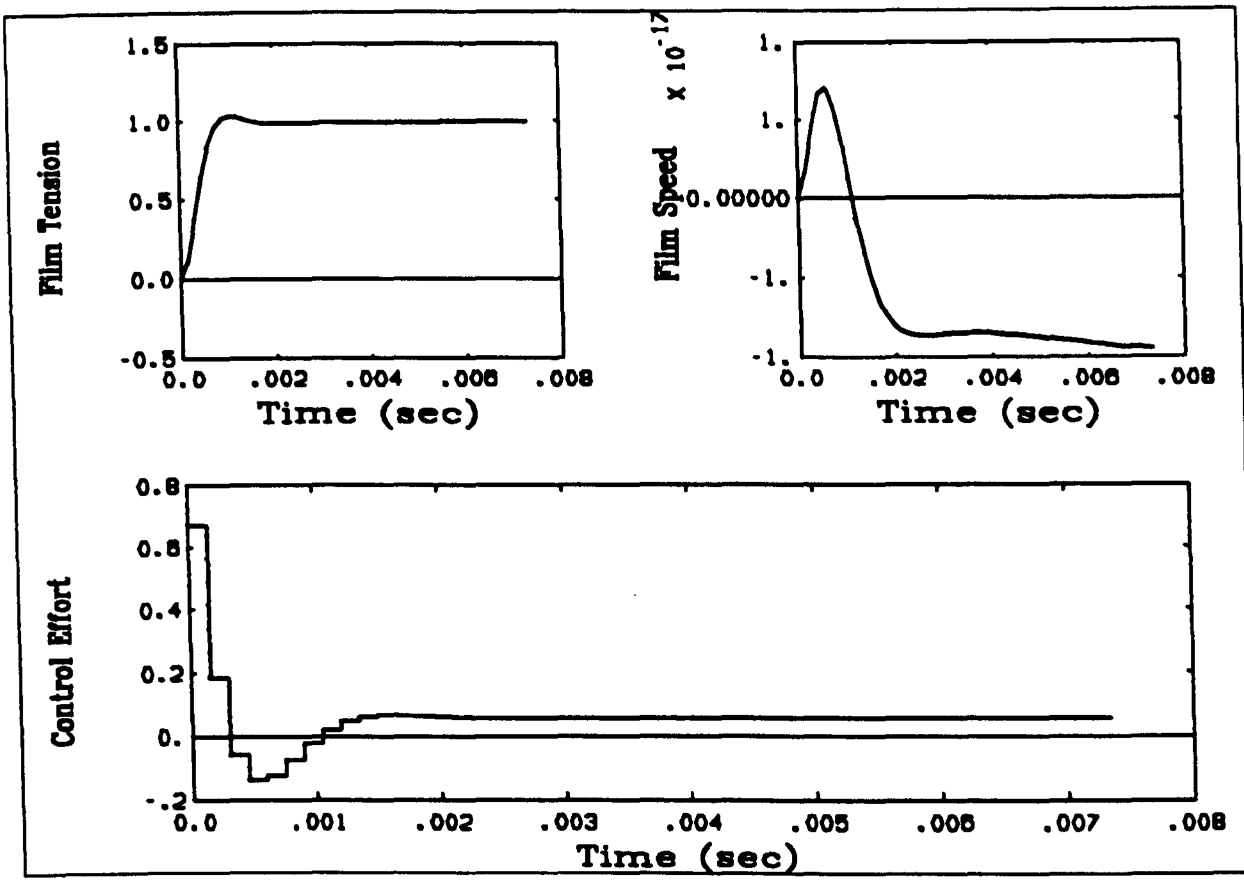

Figure 4.9 - Response to unit step in tension input

Full-state feedback with added integral control - no external disturbances

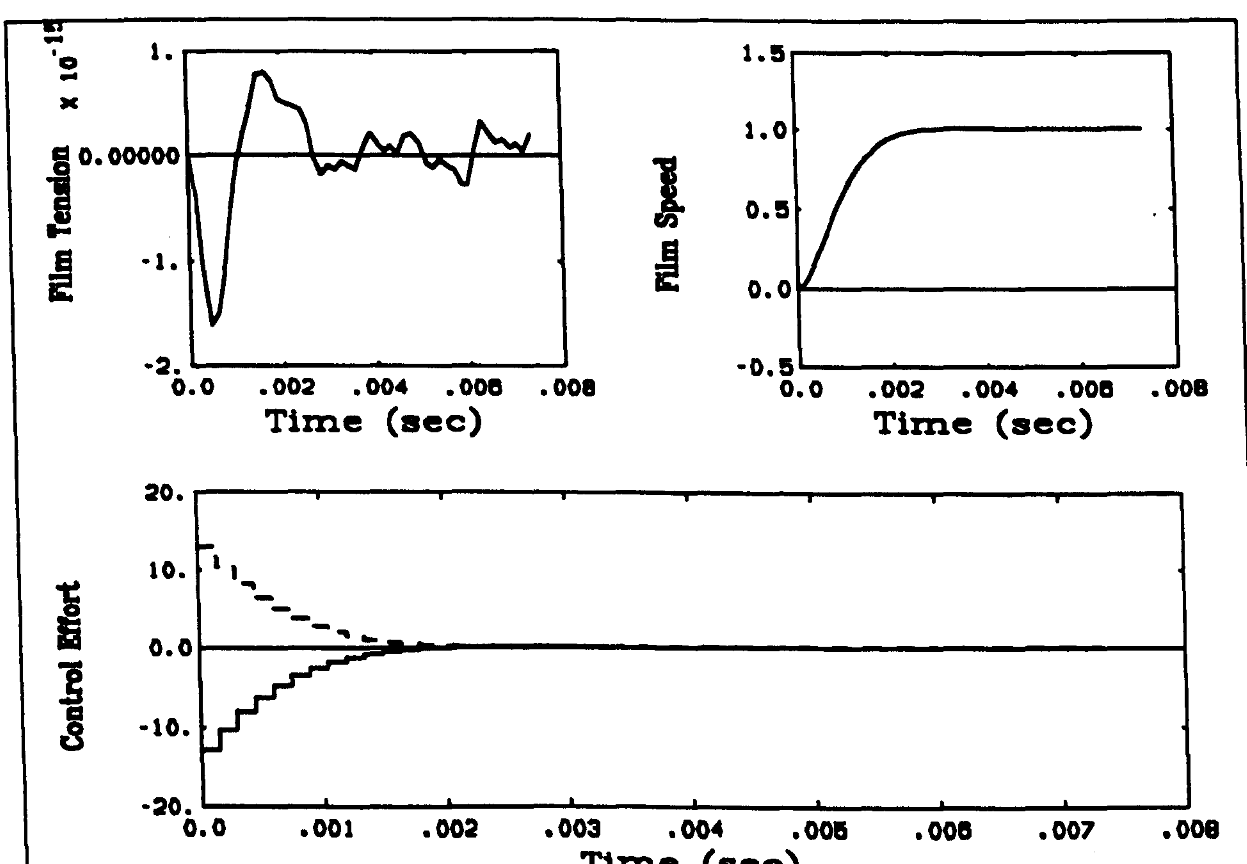

Figure 4.10 - Response to unit step input of speed

Full-state feedback with added integral control - external tension disturbances (rms 1 unit)

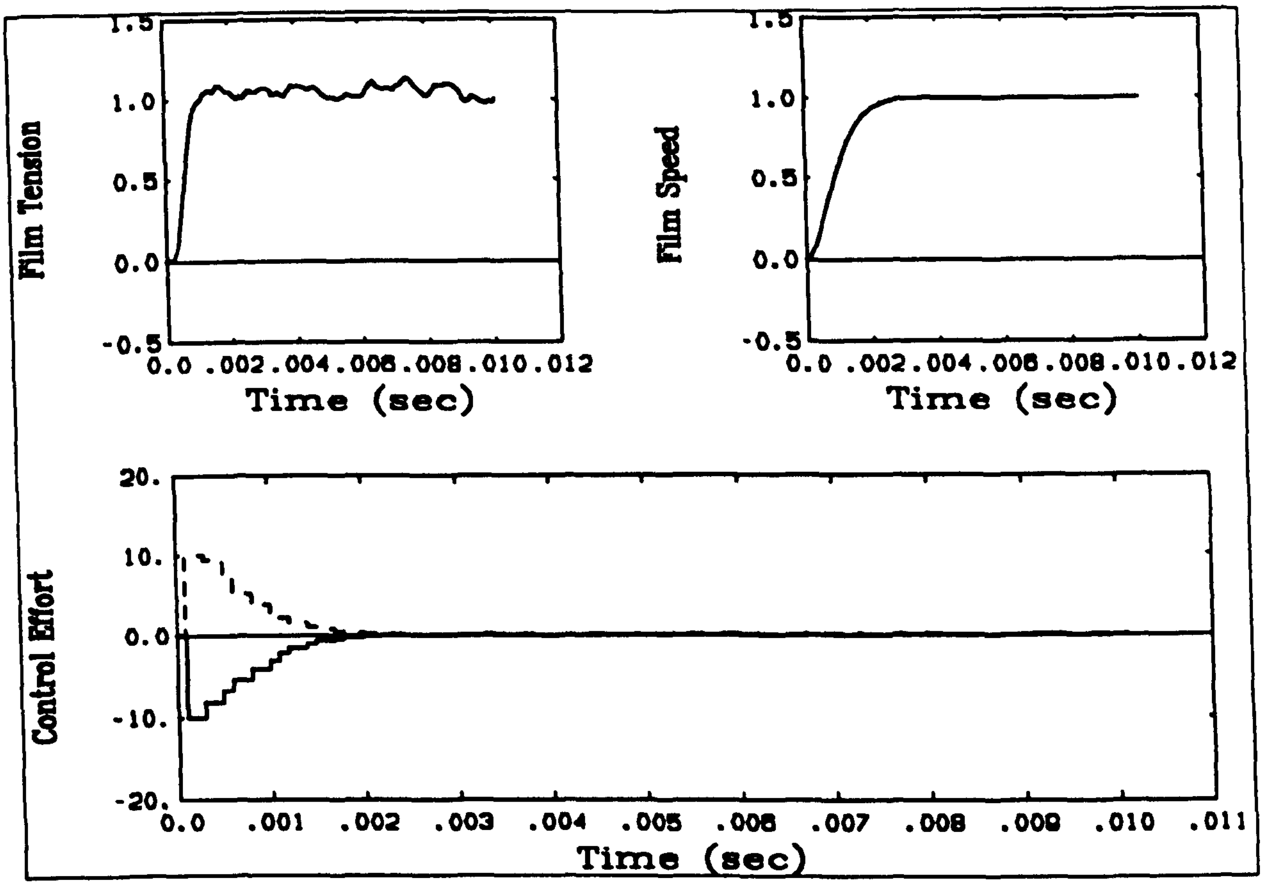

Figure 4.11 - Response to unit step in tension + speed

Full-state feedback with added integral control - process noise disturbance (i_1, i_2) (rms 1 unit)

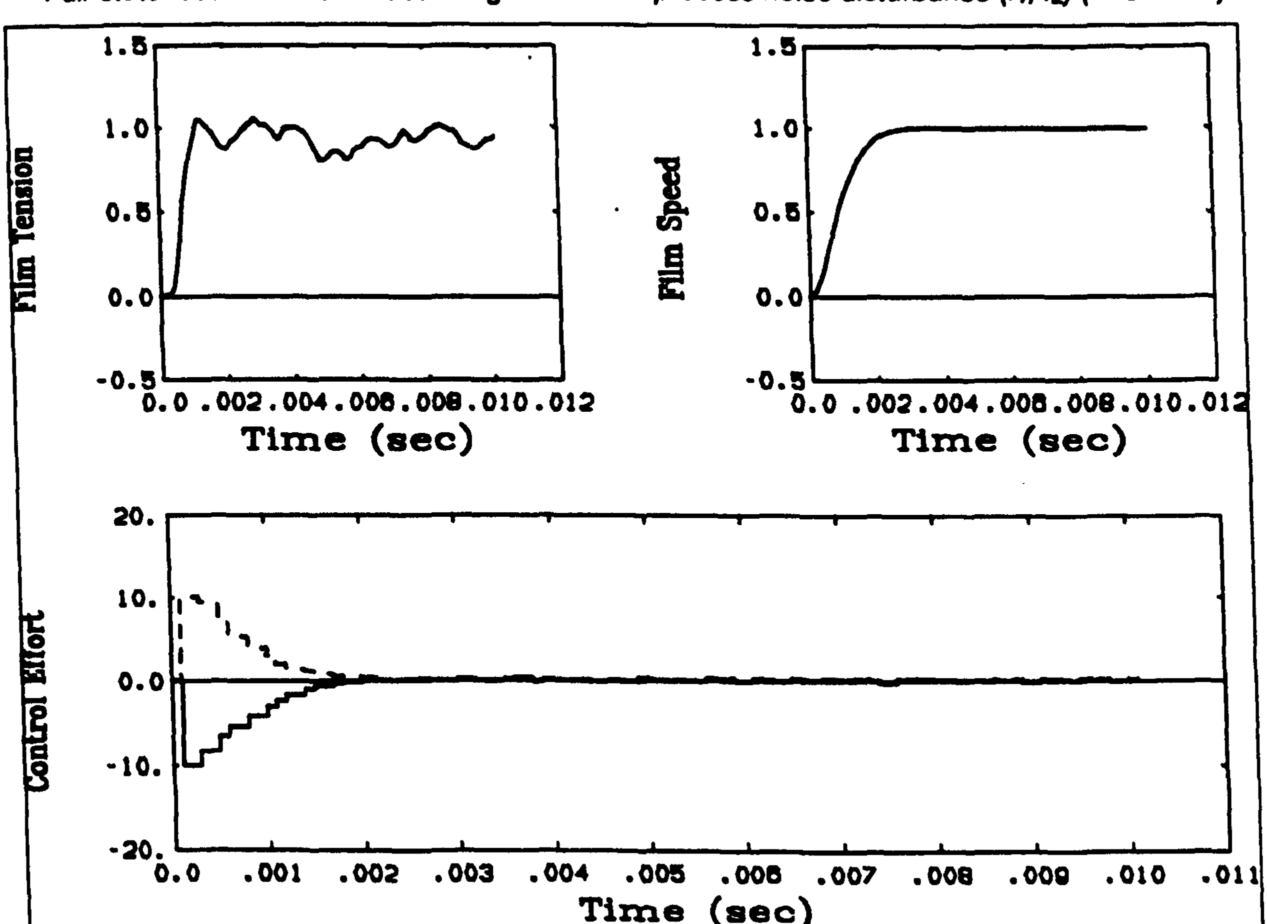

Figure 4.12 - Response to unit step in tension + speed

Using this new augmented system description a new set of feedback gains is formed given by,

$$K_a = \begin{bmatrix} 0.0151 & 0.4649 & 0.2555 & 0.2983 & 0.1378 & 0.5501 \\ 0.0151 & 0.2555 & 0.4649 & 0.1378 & 0.2983 & 0.5501 \end{bmatrix} \tag{4.22}$$

This new gain matrix can be partitioned into two gains, one for the integral state (K_I), and one for the original state (K),

$$K = \begin{bmatrix} 0.4649 & 0.2555 & 0.2983 & 0.1378 & 0.5501 \\ 0.2555 & 0.4649 & 0.1378 & 0.2983 & 0.5501 \end{bmatrix} \tag{4.23}$$

$$K_I = \begin{bmatrix} 0.0151 \\ 0.0151 \end{bmatrix} \tag{4.24}$$

From these gains, closed loop system descriptions can be formed as:

$$\Phi_{cl} = \Phi_a - \Gamma_a \times K, \text{ and} \tag{4.25}$$

$$\Gamma_{cl} = \begin{bmatrix} -T_{ref} & 0 \\ \Gamma * K * N_x & \end{bmatrix} \tag{4.26}$$

where Tref is the tension reference command.

This leads to:

$$\Phi_{cl} = \begin{bmatrix} 1.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 \\ -0.0117 & 0.3793 & -0.1987 & -0.2320 & -0.1071 & -0.4277 \\ -0.0117 & -0.1987 & 0.3793 & -0.1071 & -0.2320 & -0.4277 \\ -0.0030 & 0.3288 & -0.0584 & 0.9347 & -0.0319 & -0.1888 \\ -0.0030 & -0.0584 & 0.3288 & -0.0319 & 0.9347 & -0.1888 \\ -0.0027 & 0.1329 & 0.1329 & 0.0807 & 0.0807 & -0.8248 \end{bmatrix} \tag{4.27}$$

$$\Gamma_{cl} = \begin{bmatrix} -1.0000 & 0.0000 \\ 2.1062 & -17.6804 \\ 2.1062 & 17.6804 \\ 1.0421 & -9.1231 \\ 1.0421 & 9.1231 \\ 1.0060 & 0.0000 \end{bmatrix} \tag{4.28}$$

Figure 4.9 and 4.10 show the unit step response of this full-state feedback controller with added integral control. The tension steady state error has been reduced to meet the

Full-state feedback, added integral control and estimator - external tension disturbance (rms 1)

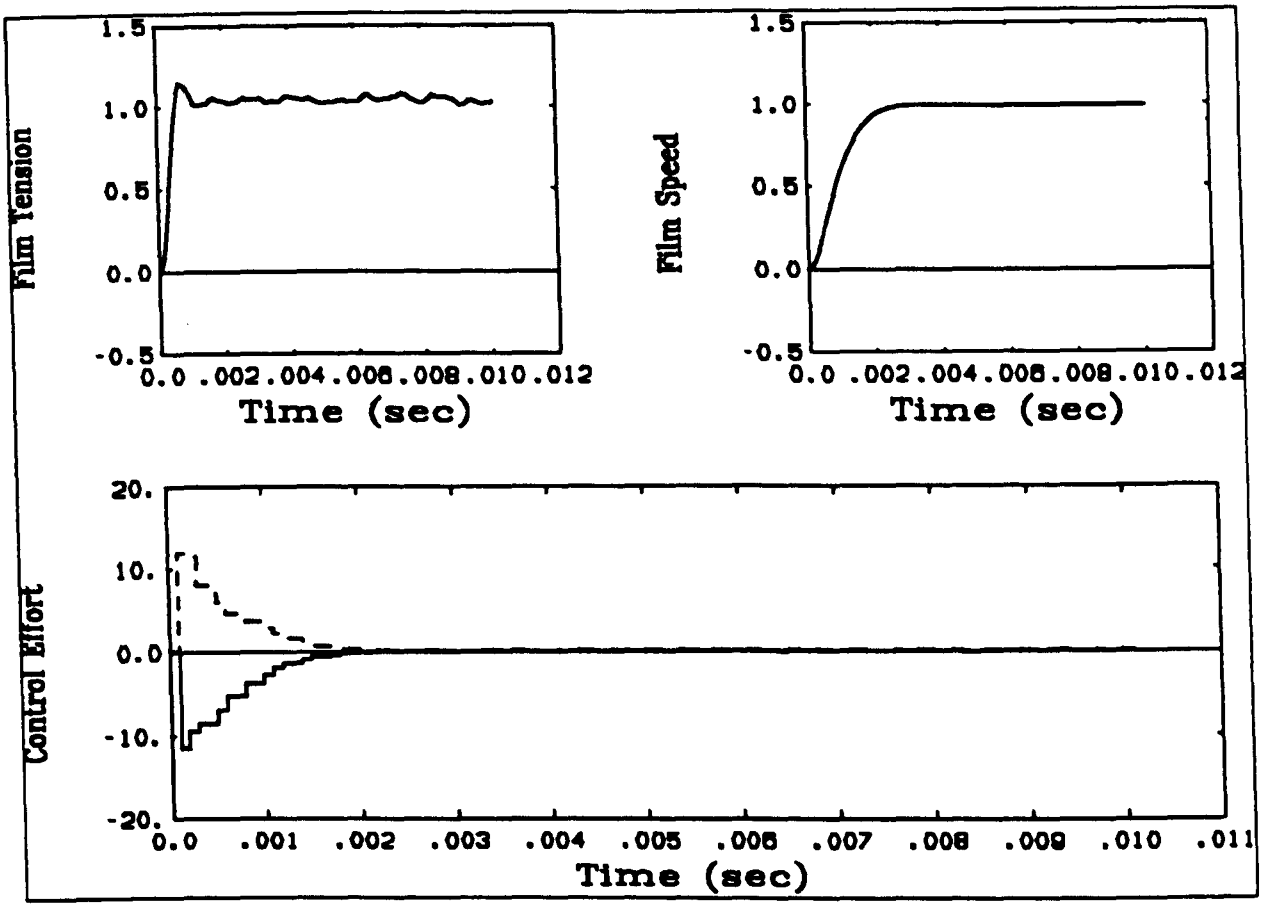

Figure 4.13 - Response to unit step in speed + tension

Full-state feedback, added integral control and estimator - process noise (i_1,i_2) (rms 1 unit)

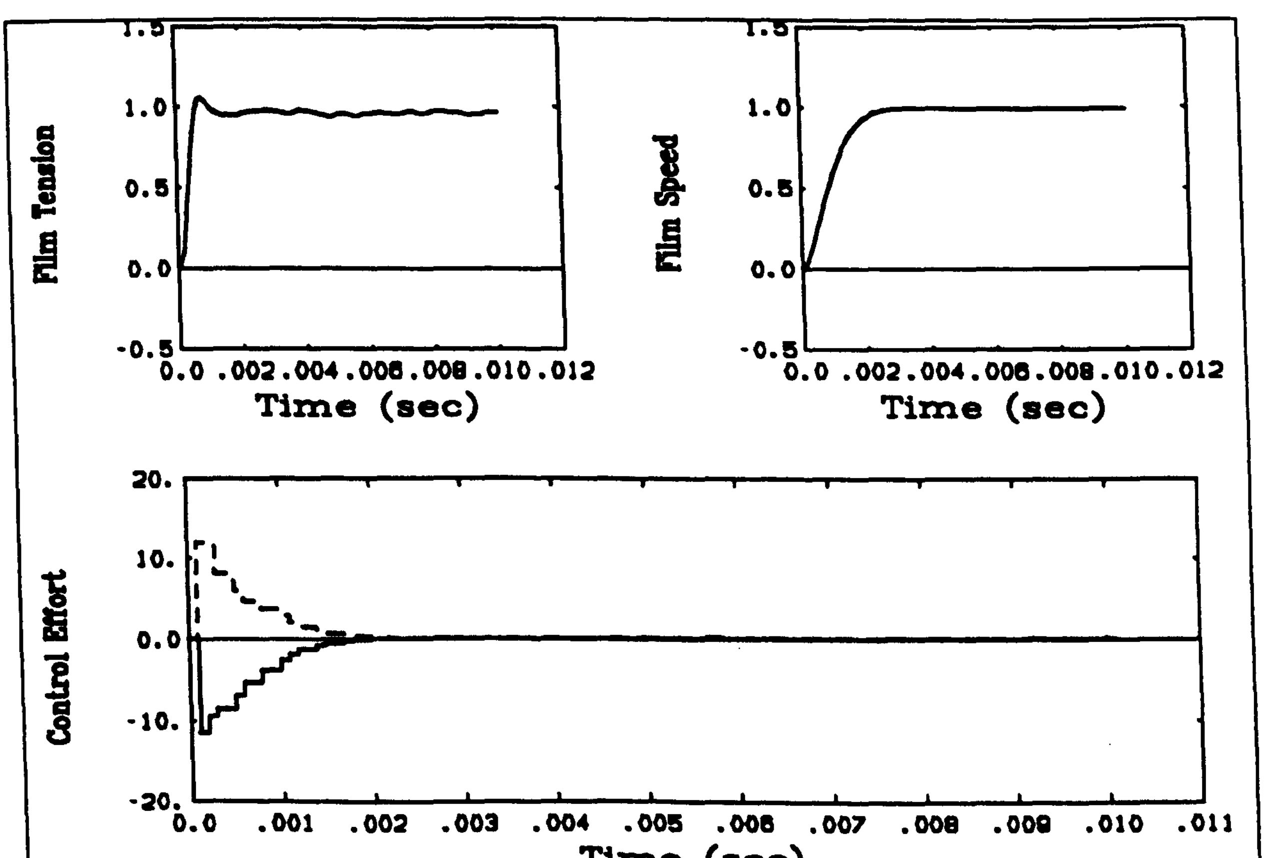

Figure 4.14 - Response to unit step in tension + speed

Full-state feedback, added integral control and estimator

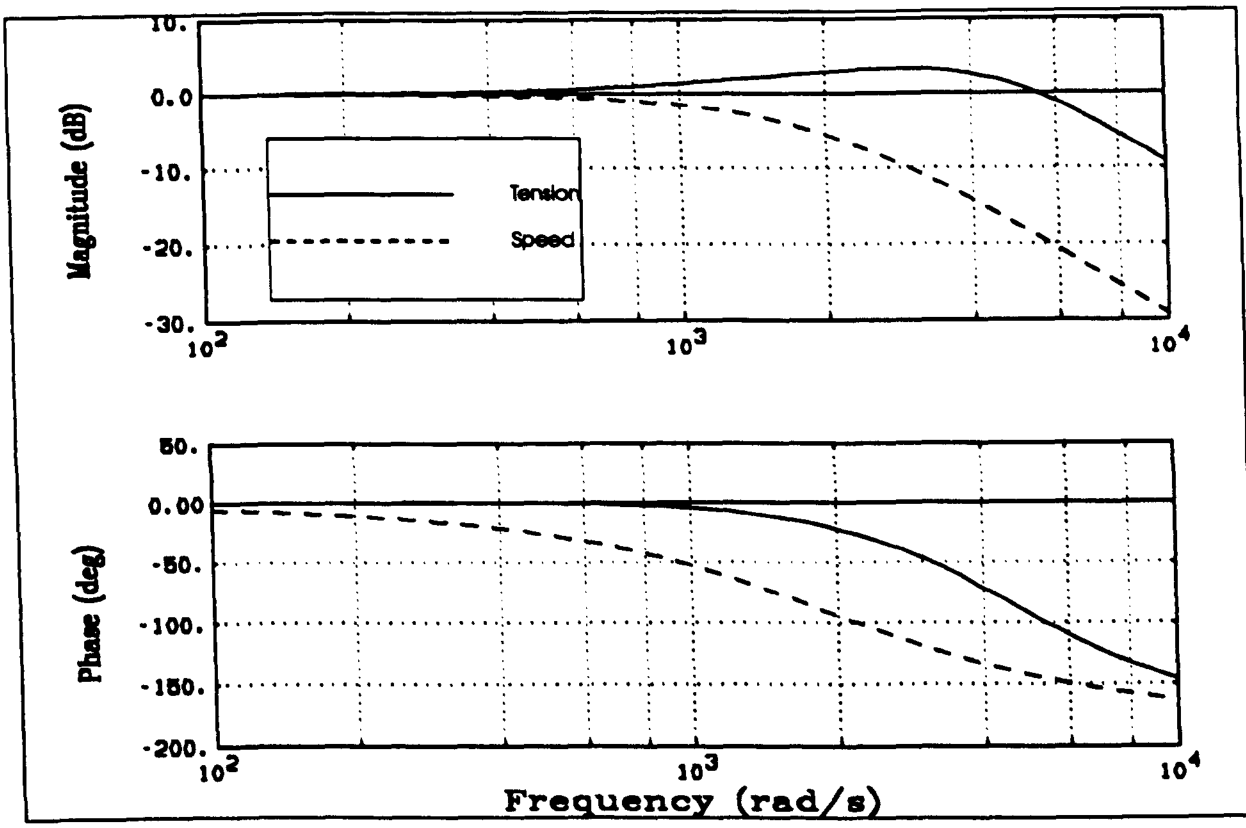

Figure 4.15 - Closed-loop frequency response

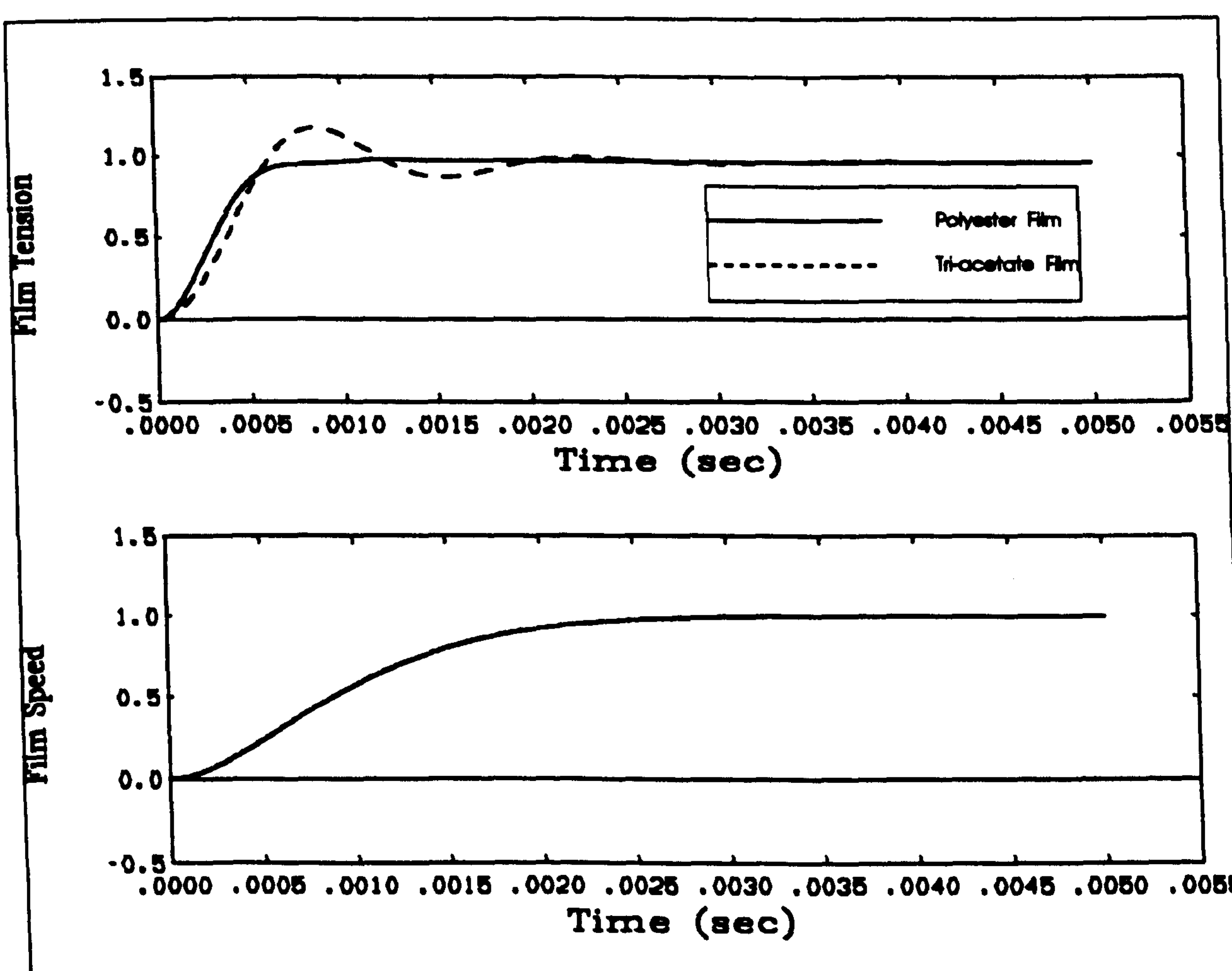

Figure 4.16 - Step response: Varying film properties

specification and the control efforts are further reduced. Adjustments to the weighting matrix have achieved this response.

At this stage we have a optimum solution for the controller that meets the system specification. This 'ideal' system has not taken into account the effects of measurement inaccuracies associated with external disturbances and sensor accuracy.

There are two main sources of disturbance,

- ☐ Process Noise - This is assumed to be associated with the control signals and enters identically to both servo drive systems.

- ☐ Tension Disturbance - This is the main source of disturbance to the system and the most important as the source of this disturbance, the film, is the couple between the two capstan drives.

Tension disturbances and process noise were added to the ACSL model of the system together with system non-linearities such as amplifier limits and tension limits.[2]

The controller was run on the ACSL model of the capstan drive via the software interface. Results showing the effect of unit step inputs on both tension and speed with the added disturbances are shown in figures 4.11 and 4.12.

The response of speed and tension show that there is no effect on the speed response of the film. This is partly due to the excellent mechanical damping from the capstan/motor assembly. The response of the tension to disturbances can be clearly seen but as in the case of the speed response, damping has reduced the effects of tension disturbance.

The next stage was to implement a Kalman filter to reduce the effects of these disturbances but retain system robustness to plant parameter changes.

---

2 Tension in the film can never be negative.

4.3.4.1 Estimator design

As stated previously the only mechanical link between the two drive capstans is the film. This is also the main source of disturbance input to the system. The high stiffness of motion picture film together with its small cross section allows for much tension fluctuation for small displacements in the film. The amount of free film between transport rollers and the capstan drive also is an important factor when considering film vibration. Any out of 'true' rollers can cause edge picking of the film which is transmitted into the film. These effects have been simulated in the non-linear model as random vibrations although in practice they might follow a cyclic pattern.

One solution that aims to reduce the effect of process noise is the Kalman filter, see section 2.5.2 .The Kalman filter estimator is based on a model of the system. Without process noise or disturbances the estimator will receive the same control input as the plant and no estimator error will be generated. The same process noise used in the last section will be used to test the estimator. As stated previously the tension measurement is directly proportional to the sum of the control input, effectively current, measurement. The film speed is directly measured.

The sensor noise matrix $\boldsymbol{R}_v$ describes the rms error level of the measurement. The rms tension measurement is 0.1N. The speed measurement is more accurate with a rms accuracy of 0.001m/s. The sensor noise matrix can be written as

$$\mathbf{R_v} = \begin{bmatrix} 0.01 & 0 \\ 0 & 0.000001 \end{bmatrix} \tag{4.29}$$

The process noise matrix acts directly on the continuous part of the system and in this case is assumed to enter the control signal input identically. After an initial arbitrary choice and some testing to obtain the best estimator performance the following process noise matrix was formed,

$$\mathbf{R_w} = \begin{bmatrix} 0.001 & 0 \\ 0 & 0.001 \end{bmatrix} \tag{4.30}$$

The estimator was based on the plant model described by (4.8) and resulted in the gain matrix,

$$\mathbf{L} = \begin{bmatrix} 0.0600 & -0.0843 \\ 0.0061 & 0.0180 \\ 0.2193 & -1.5626 \\ -0.0146 & 1.4198 \\ 0.2096 & -0.1473 \end{bmatrix} \tag{4.31}$$

The unit response shown in figures 4.13 and 4.4 shows how the estimator has reduced the measurement noise and process noise. The poles of the model based estimator have been chosen to be twice as fast as the original system. Again it can be seen that the speed response is unaffected by these disturbances, effectively damped out by the mechanical elements of the capstan drive. The final controller test is one of its robustness. The main parameter change that is important to consider in the film industry is the different types of film that are used. The system has different behaviour with polyester and tri-acetate film. From the calculations shown in appendix A, on the determination of film properties, two plots can be made for each type of film, (tri-acetate and polyester) i.e. two different film stiffness and damping coefficients. Figure 4.16 shows the response of the system using the two different types of film. Both film types have similar stiffness coefficients but polyester film has a lower damping coefficient (5.1 N/m/s) compared to that of tri-acetate film (14.0 N/m/s). This lower damping is clearly seen in the unit step response curve. The response of this film type still remains within the system specification. The system can be said to be robust for change in plant parameters, external disturbances, and process noise.

Summary

This chapter has dealt with the formulation of state-space matrices to describe the capstan drive system. This state-space description was formed by linearising the equations of motion of the various components of the plant. The linear description was used in a CASD package (Ctrl-C) to develop several controller strategies based on LQR and state-feedback methologies. Three main strategies were developed, full-state feedback, full-state feed-back with added integral control and finally full-state feedback with added integral control plus estimator. The three controller designs were tested on both the linear and the non-linear description of the plant, the non-linear system included external disturbances, process noise and saturation limits.

The results showed that although the full-state feedback gave an adequate response the addition of integral control of the tension gave zero steady state error in response to external disturbances. The speed response of the system remained within the specification for all controller designs. This was partly due to the mechanical damping of the system (capstan and motor inertia) and the good decoupling from the tension. The use of the estimator (Kalman filter) gave the system excellent rejection to tension disturbances and process noise.

The next chapter deals with the implementation of these algorithms on a digital controller. The systems described work well in simulation where the sample time has been chosen to reflect the system performance not the implementation criteria. The following work will show how these relatively complex algorithms requiring fast computational times can be realised using parallel processing techniques based on the transputer.

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Chapter 5

Control Implementation & Experimental Testing

5.1 Introduction

For complete validation of the model and derived control algorithms it was necessary to design and construct a prototype test rig. This test rig would have to mirror the copying process that is currently undertaken by conventional printing machines, and at the same time incorporate the new design concepts previously mentioned. A process of actuator selection was undertaken based on the specification of the control system together with the sensor selection that satisfied the controller design.

A controller design based on the strategy formulated in Chapter 4 has been implemented on the transputer system to maximise system performance, reducing computational time and increasing the flexibility of the system. Using the control block diagrams, data flow diagrams were formed. This has enabled potential signal bottlenecks to be identified. Using these data flow diagrams transputer architectures have been implemented that maximise data flow through the system allowing greater computational tasks to be achieved in a shorter time period.

5.2 Capstan Drive

Plate 5.1 shows the final prototype test rig used for system testing. The hardware configuration, figure 5.1, and system design have been divided into several areas.

5.2.1 Capstan transport mechanism

Each capstan drive consists of a film transport roller fixed to a shaft which is coupled to a brushless motor via a flexible coupling. The flexible coupling has the effect of reducing backlash from the main motor and compensating for any effects of shaft mis-alignment.

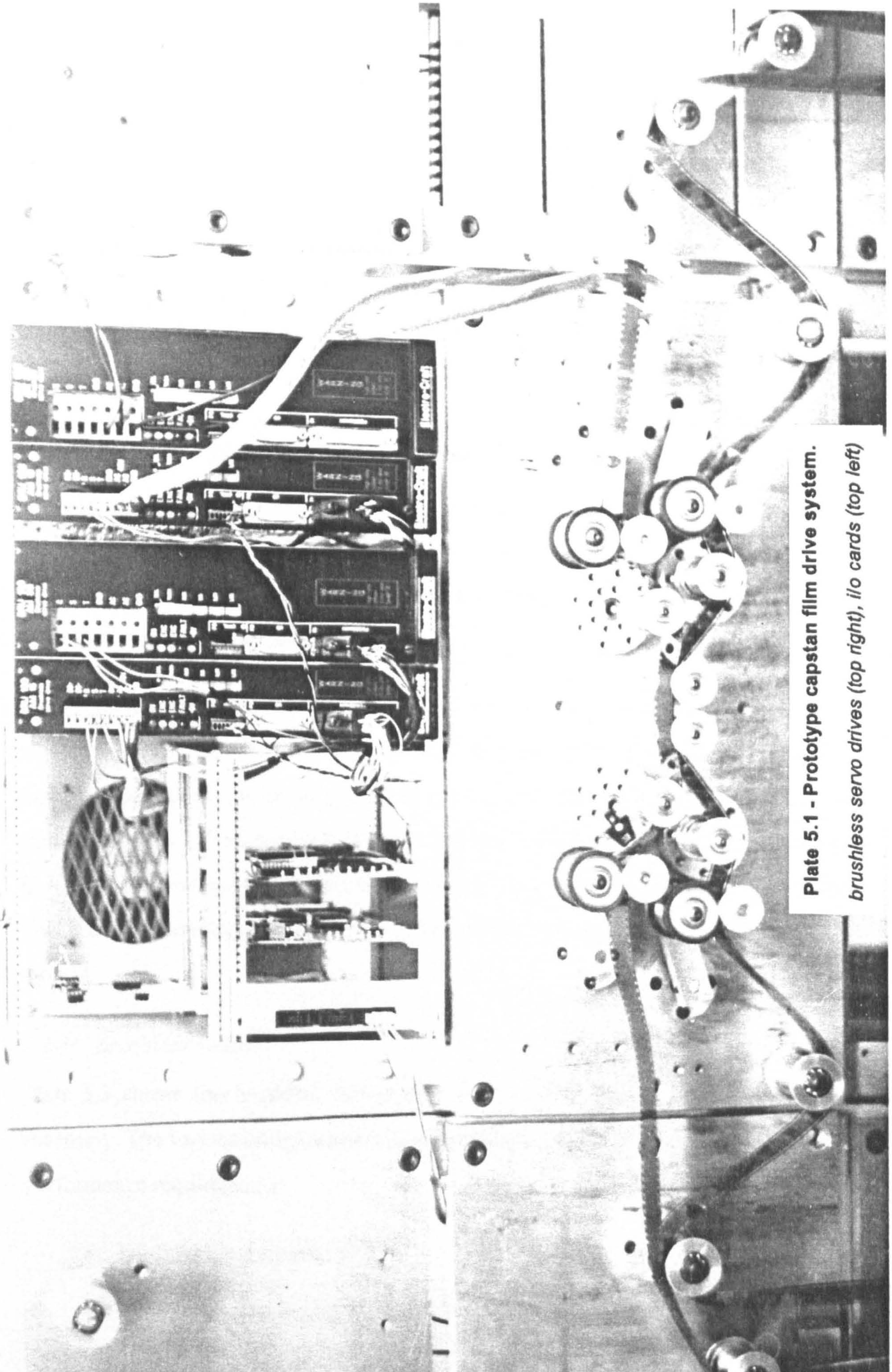

Plate 5.1 - Prototype capstan film drive system.
brushless servo drives (top right), i/o cards (top left)

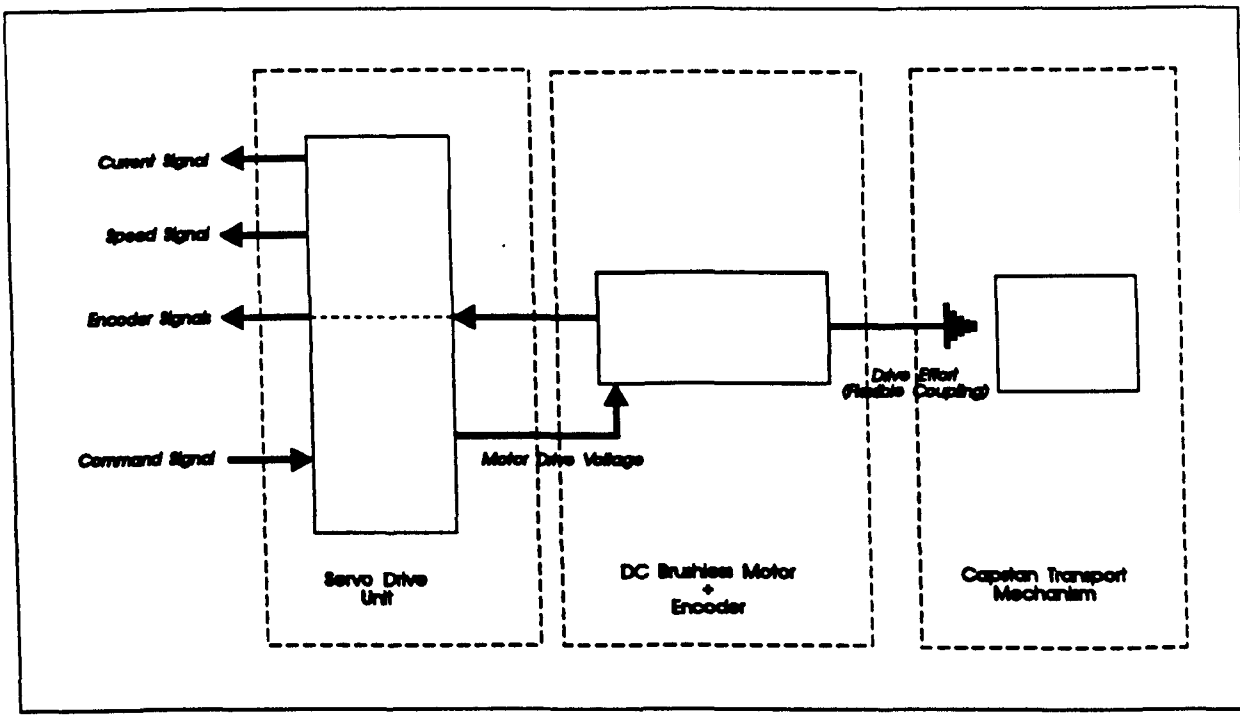

Figure 5.1 - Hardware elements of capstan drive

Tests were made on the motor-coupling-capstan assembly to identify the effect of the coupling on the system. Figure 5.2 shows the response tests on this system. The coupling can be seen as the second order system effect with relatively low magnitude (-50 db). This effect has been ignored in the simulation tests.

A hold down roller ensures that film does not slip while being transported. The hold down roller consists of a roller with rubber tread on either side, plate 5.2. The rubber tread allows the film to be driven only on the perforated edges of the film, so as not to damage the film emulsion. Guide rollers between the two associated capstan drives (positive or negative film path) are mounted on rotating discs to allow the position of the rollers to be altered. This is used to investigate the effect of different film paths and film/roller wrap on the film motion.

5.2.2 Brushless motors

Plate 5.3 shows the brushless motor mounted at the rear of the printing head plate assembly. The various design constraints from the specification have given the following performance requirements:

- Bi-directional speed control
- Low inertia servo motor able to handle acceleration demands one order of magnitude larger than the continuous torque

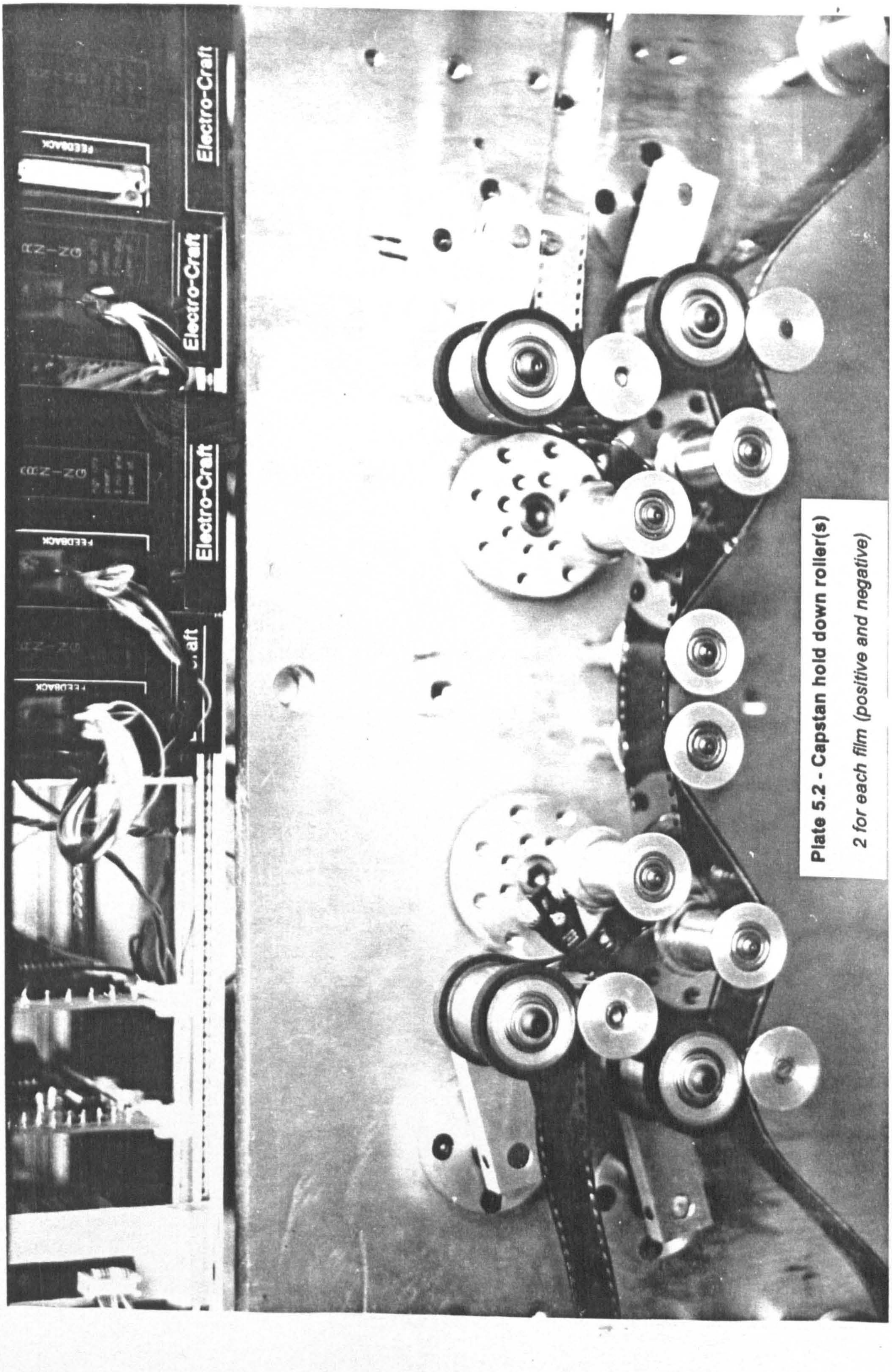

Plate 5.2 - Capstan hold down roller(s)

2 for each film (positive and negative)

Plate 5.3 - Brushless DC motor for capstan drive
connected via flexible coupling

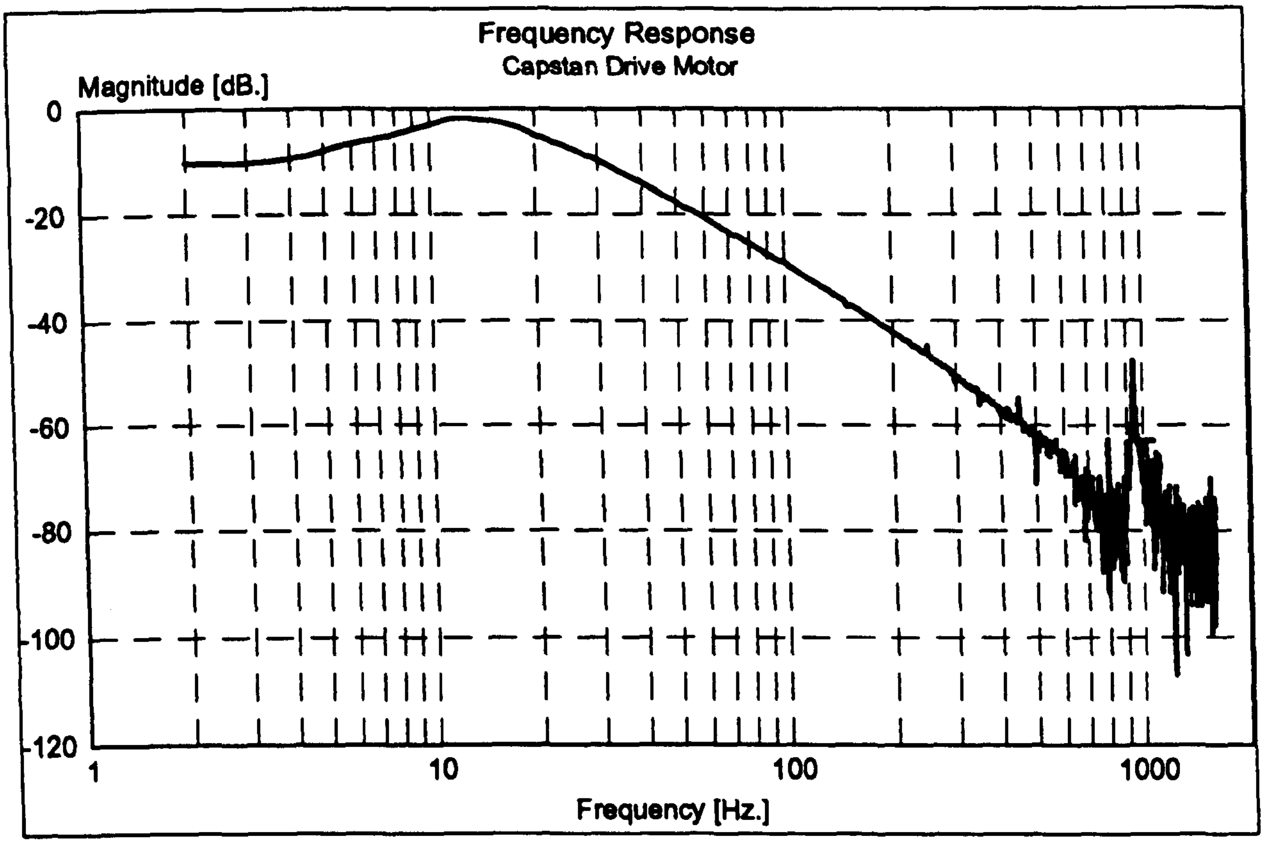

Figure 5.2 - Frequency response test

[motor + coupling + capstan]

- Servo motors with low torque-ripple
- High running speeds (6000-10,000 rev/min)

These requirements have led to the selection of a Brushless DC motor together with a compatible Servo Drive Unit. Appendix (D) details the full motor specification. Each motor has an optical encoder fitted. Each module is fitted with a 1000 line optical encoder disc and two sensors mounted 90 degrees out of phase allowing quadrature counts to be obtained.

5.2.3 Servo drive unit

The servo drive unit is a dynamic velocity controller providing trapezoidal drive for three-phase motors with hall effect commutation sensing, and two-channel optical encoders for velocity feedback. It has low torque ripple and torque disturbance. The drive unit can operate in torque mode producing a current signal proportional to the amplitude and polarity of a drive signal. A full specification is given in Appendix(D). The unit supports two modes of operation:

☐ Velocity mode - Velocity mode is where the command signal is balanced at the summing junction of the first control loop against a signal which constitutes tacho feedback. The difference between the two signals is amplified and limited, and becomes the torque command. This in turn is balanced at the summing junction of the second (inner) control loop against the current feedback signal. The error is amplified and used to drive the PWM power stage to control power to the motor. The velocity amplifier thus provides the command for the torque amplifier.

☐ Torque mode - In torque mode the tacho is disconnected and the velocity loop amplifier is set to unity gain (by connecting a local feedback resistor). Thus any command on the velocity command input is passed through to the torque command unchanged.

Encoder pulses from the motor consist of two channels A and B 90 degrees out of phase, and an index pulse. At each transition of the encoder (rising or falling, A or B) a decoding circuit computes the direction and at the next system clock edge will set an output for 'up' or 'down' accordingly. At the next system clock edge this will be reset, so if the encoder is rotating in a clockwise direction at a steady speed there will be a train of 'up' pulses one clock cycle wide. The limit of this is where two transitions occur in less than two complete clock cycles, in which case an error is generated (because the second transition would be missed). Thus the maximum output rate of the circuit is one pulse every two clock cycles, a 50% duty cycle. Encoder hardware details are given in appendix D.

The clock frequency is 1 MHz., so the maximum output frequency is 500 kHz.. In practice this is limited to 400 kHz. to avoid errors due to quadrature imperfections in the encoder. Since the output pulse is generated for every transition of the encoder outputs, and there are four of these per line, the maximum line frequency is 100 kHz..

Thus a 100 kHz. output signal from the encoder will generate 1 microsecond wide pulses at the rate of 400 kHz.. This signal is applied to a switch which switches a precision 10 volt signal onto the output filter, so the average of the signal will be approximately 4 volts.

5.3 Interface Hardware

The interfaces allow communication between the digital controller and the plant. Table

Signal	Type	Sense/Use	
Encoder A	TTL	TRUE=HIGH	OUT
Encoder B	TTL	TRUE=HIGH	OUT
Motor Current	Analogue	5 Volts (Peak)	OUT
Control Signal	Analogue	+/- 10 Volts	IN

Table 5.1 - Connections between plant and controller

5.1 lists the various control signals associated with one drive element of the dual capstan film drive.

☐ Pulse Processing - To achieve fast i/o it was decided to use a memory mapped pulse processor that could undertake extra processing of data relieving the main i/o processor of some of its computational loading. The pulse processor has many useful features:

- 15 commands for executing pulse i/o operation
- Up to 16 commands are programmable from the MPU into the function table (RAM)
- 24 16-bit universal registers
- 16 i/o terminals with 8 internal registers for pulse i/o control
- Interrupts can occur at the falling edge or rising edge of all pulse signals
- Pulse width resolution is 5 μs when executing 16 commands at 4 MHz operation frequency.

This universal processor has allowed many computational intensive operations to be carried out such as pulse width measurement,pulse cycle measurement, phase difference measurement and counting of two-phase pulse signals. The two-phase pulse signal counting has allowed quadrature counting from the two channels of the encoder.

☐ Analog Input - The analog signals associated with the system were interfaced using multiplexed and demultiplexed serial i/o devices connected to the transputer controller via the serial links. The decision to use multiplexed i/o devices was made on an affordability rather than a practical decision. The 'ideal' solution to the interfacing of these signals is discussed in later chapters. The analogue signals from the servo drives that indicate motor current are interfaced to the controller via a multiplexed link adapter device. These current signals are used to estimate the tension in the film (sum of current signals).

- Analog Output - The output to the system are voltages that represent the control signals for the motor drive units, (2 in total for the capstan drive). Ideally we would have liked to output these from 2 separate DAC devices each connected to a separate link (or processor). This would reduce the added computation time associated with de-multiplexing processes and conform more to the design of the system as a data flow problem. Unfortunately limited hardware has only allowed the use of a single link DAC with de-multiplexed channels. This however has still given the performance necessary to fulfil the system specification.

The total system was designed to be of modular format with most of the devices being eurocard or TRAM (TRAnsputer Module) specification. This modular approach has allowed quick development of the prototype system together with the added flexibility of using replaceable modules.

5.4 System Configuration and Testing

One of the limitations (at present) is the number of links on each transputer, typically 4. To maximise data transfer between processors,the links, which are autonomous DMA engines, must be kept as busy as possible. To avoid links waiting on the processor or vice versa, the link communication must be decoupled from the main processing. This is achieved by running the input and output processes in parallel with the main routine. These input and output processes can be considered as simple buffers, allowing the processor to perform computation on one set of data, whilst concurrently inputting a new set, and outputting the previous set.

REAL32 Operation	Processor Cycles	
	IMS T222 (50ns)	IMS T800 (50ns)
+ -	530	7
*	650	11
/	1000	17

Table 5.2 - Floating point arithmetic performance

```
PAR
  buffer(adc.data,in.alg)
  main(in.alg,out.alg)
  buffer(out.alg,dac.data)
```

The input processor as described above is a 16-bit transputer. The data from the processes running on this transputer must be kept in integer format until transferred to the processes that deal with the computational intensive control algorithms. These processes run on the 32-bit T800 transputer. It is possible to do a type conversion (INTTOREAL32 - software run time package) on the 16-bit processor but the overhead associated with computational time makes it unsuitable for real-time processing. Table 5.2 summarises the comparison in performance for some floating point operations.

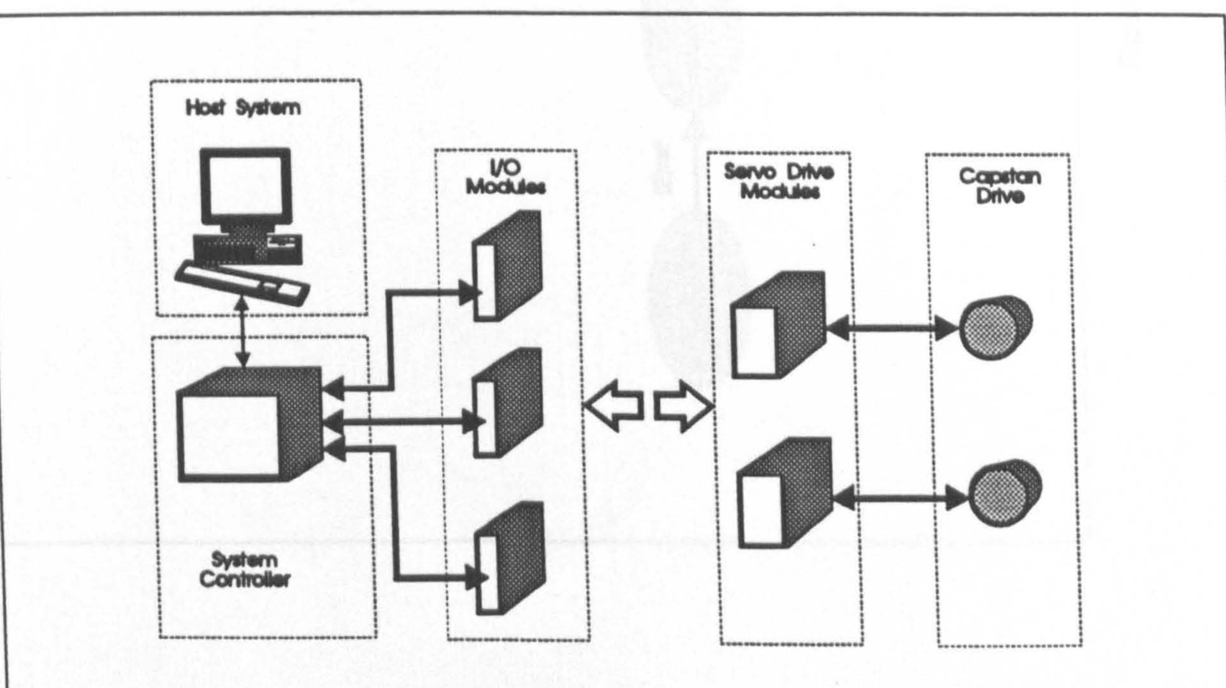

Figure 5.3 - Capstan system: Modular configuration

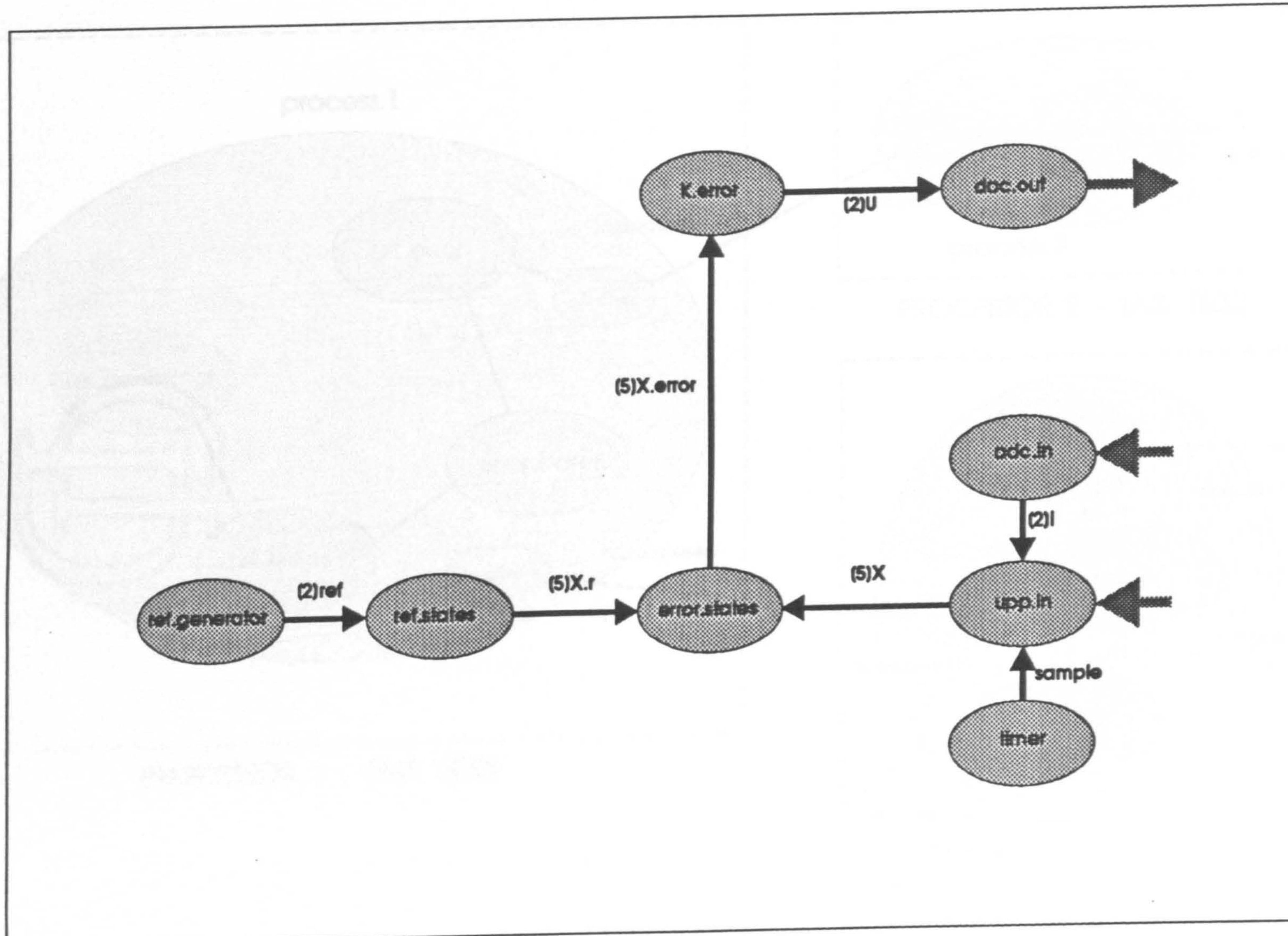

Figure 5.4 - Process +data flow configuration

Full-state feed-back controller

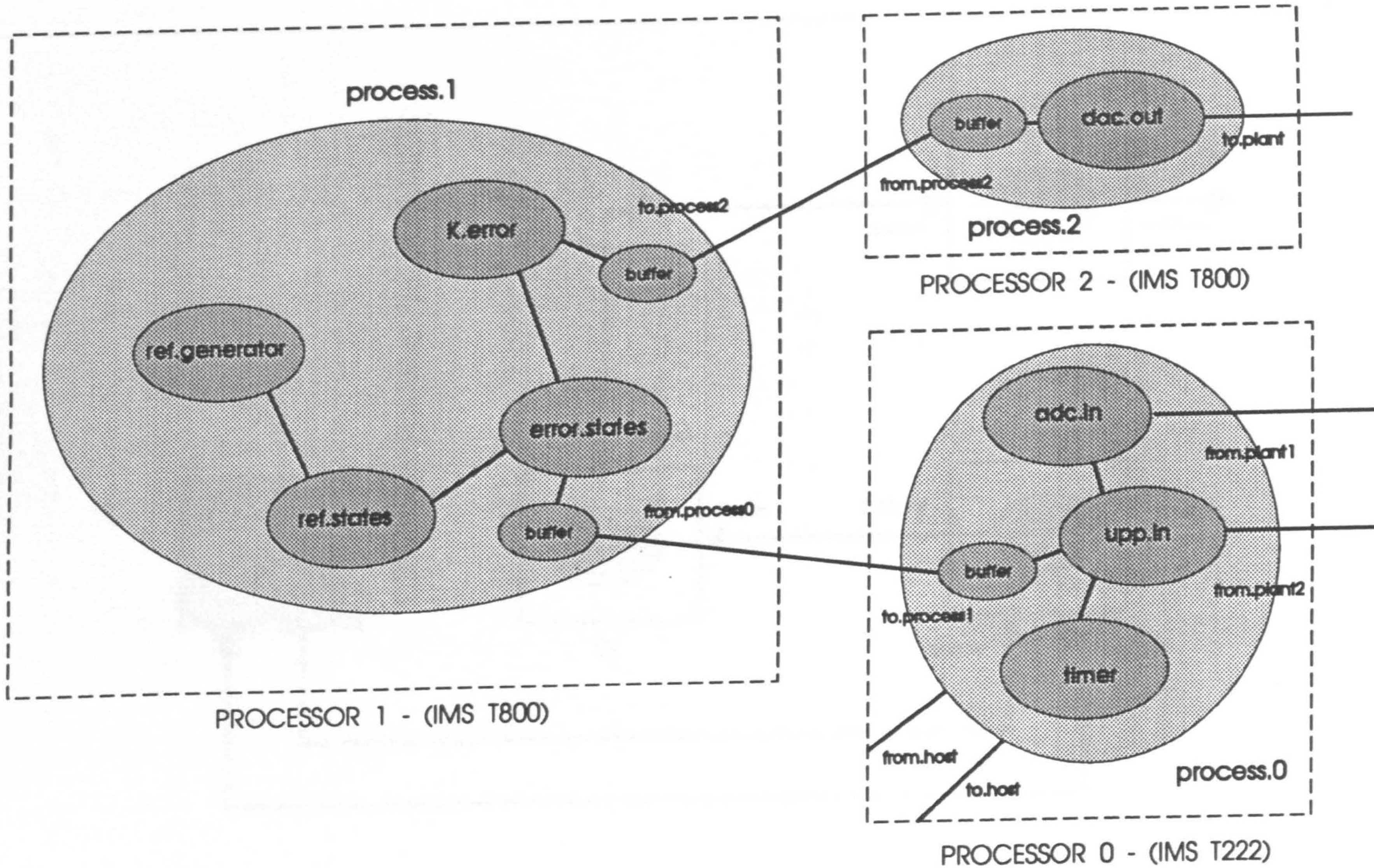

Figure 5.5 - Processor configuration
full-state feedback controller

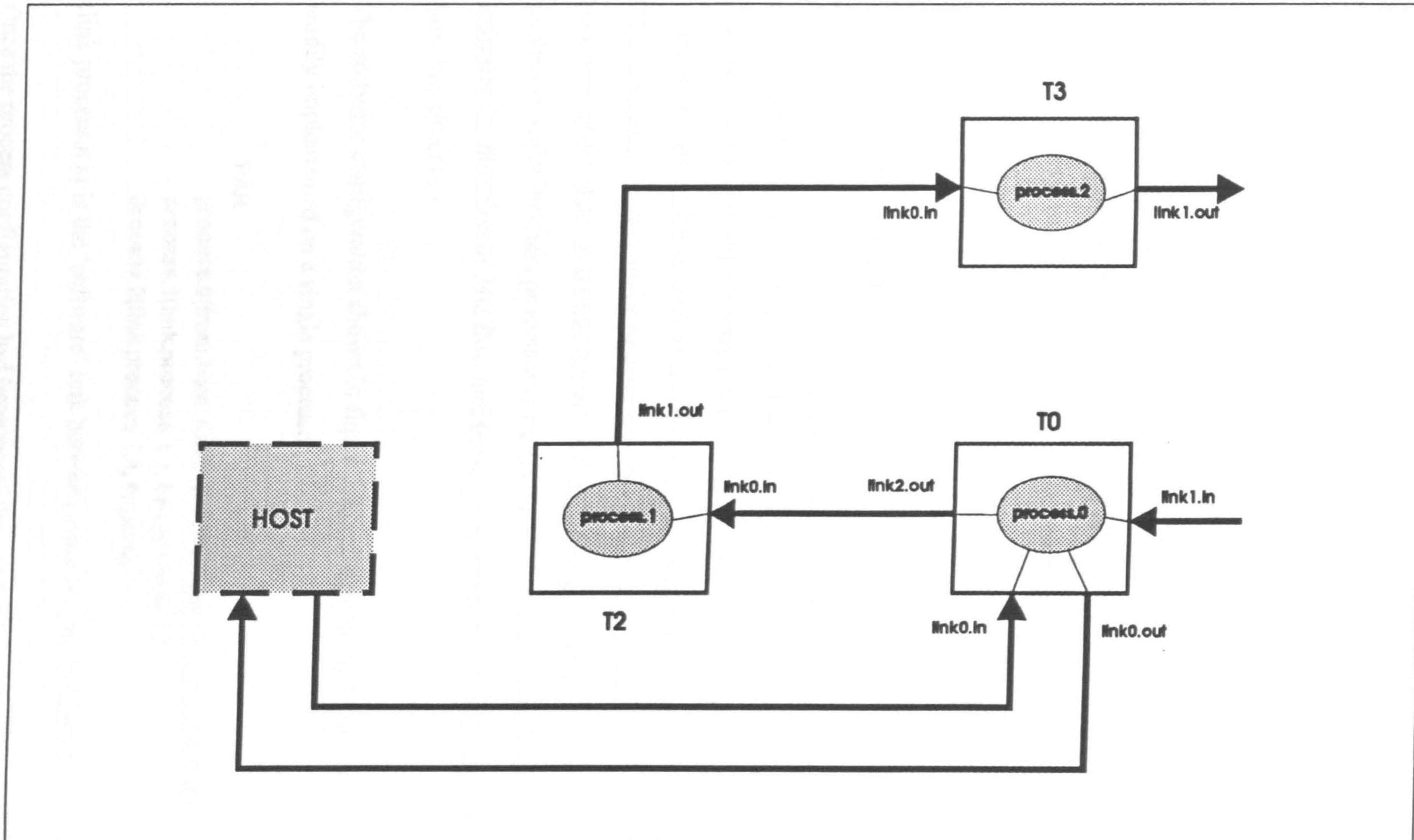

Figure 5.6 - Transputer hardware configuration

full-state feedback controller

The capstan drive consists of three main parts:

- System Plant - This is the physical system to be controlled.
- System Controller - The digital implementation of the control algorithms.
- System Host - The host sub-system i.e. user/system interface.

The configuration and the various interconnections are shown in figure 5.3.

To allow experimental data to be obtained a data acquisition routine was written. This was executed on a single transputer with data stored in local memory before being transferred to the host-sub system. The data acquisition system was run concurrently with the main control system. This ensured that there was no degradation of the execution of the control algorithm.

5.4.1 Full-state feedback

Figure 5.4 shows the data flow diagram for full state feedback control. This system is relatively easily implemented on the transputer and can be configured as shown in figure 5.5. Each processor has a single main process - **process.*n*** - where ***n*** is the processor number. Within each each of the main processes are the allocated blocks of the controller. Also contained in this main process are the link buffer processes. These link buffer processes allow data to be transferred to the link engine ready for transfer to another processor whilst the main processor is working on a new set of data. Each 'software' link indicates the direction of data flow and the target process, e.g. **to.process1** indicates data flow into process.1.

The software configuration shown in figure 5.4, i.e. without multiple processors, can be readily implemented on a single processor,

```
PAR
    process.0(from.host, to.host, from.plant, link.process.1.2)
    process.1(link.process.1.2, link.process.2.3)
    process.2(link.process.2.3, to,plant)
```

(link.process.*n.m* is the 'software' link between process *n* and process *m).*

Once the process configuration had been tested the configuration onto multiple processors could proceed. Each 'software' link on each main process is assigned a 'hardware' (physical) link on each processor, e.g. for process.0 - the outputing 'software' link to.process1 is assigned to the 'hardware' link link2.out on processor 0 (T0); the inputting 'software' link from.process0 is assigned the 'hardware' link link0.in on processor 1 (T1). This can be summarised in the following Occam configuration code and figures 5.5 - 5.6,

```
PLACED PAR
  PROCESSOR 0 T222
    PLACE from.host AT link0.in:
    PLACE to.host AT link0.out:
    PLACE from.plant AT link1.in:
    PLACE to.process1 AT link2.out:
    process.0(from.host, to.host, from.plant, to.process1)
  PROCESSOR 1 T800
    PLACE from.process0 AT link0.in:
    PLACE to.process2 AT link1.out:
    process.1(from.process0,to.process2)
  PROCESSOR 2 T800
    PLACE from.process2 AT link0.in:
    PLACE to.plant AT link1.out:
    process.2(from.process2, to.plant)
```

Benchmark timing and processor activity routines were used to obtain the figures shown in table (5.3),

The total execution time for the complete controller was calculated by letting the controller 'free-run' i.e. no sample period, and observing the control signal output from the ADC. The execution time was found to be 115 μs.This total time included not only the individual process execution times but also the time taken for block data transfer over the processor links.

n	Processor *n* % Activity	Process.*n* Execution Time (μs)
0	15%	20
1	100%	80
2	20%	20
Total Execution Time μs	115	

Table 5.3 - Controller performance figures

Full-state feedback

The process consuming the most processor time is the control calculation (process.1). This process consists mainly of REAL32 floating point arithmetic. To minimise link data transmission overheads the system state data was passed from one processor to another, (via buffer processes), in array blocks. This method led to a reduction in the amount of times a individual processor had to open and close link communications.

Figure 5.7 shows the response of the system to a step input of tension and speed for both the experimental and simulation tests. The results show that the rise time and steady state error for both the simulation and experimental results are similar. Stiction caused by the capstan hold-down roller can be seen in the film speed curve as an initial response lag. At constant running speed this stiction effect would be negligible. The slight discrepancy in the speed and tension steady-state error was due to a build up of tolerances on the mechanical items, particularly the capstan rollers. The system could easily be calibrated to overcome this error. Tension fluctuations are clearly evident in the experimental results, this could be due to film dynamics but as the tension measurement is obtained from the

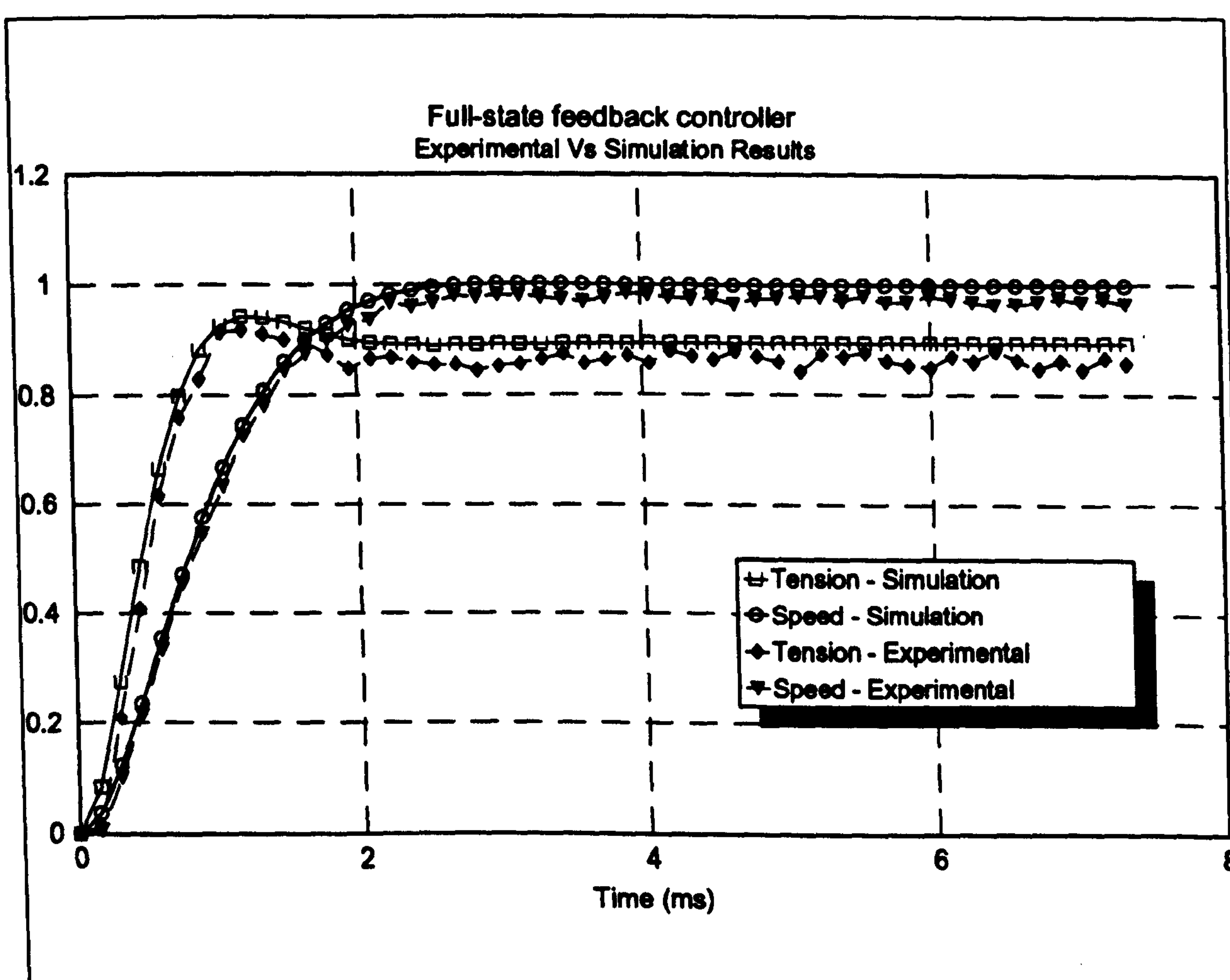

Figure 5.7 - Unit step response for tension/speed

summation of the two current readings the following reason is more plausible. The control effort experimental data was measured from the servo amplifier system. This current measurement is obtained by using a low resistance sensing resistor on the current feedback amplifier. The noise associated with this output is typical of current measurement. The film dynamics were studied by strobing the film during constant running speed. Tension fluctuations shown in the experimental data could not be seen, pointing to the current measurement as the source of noise.

5.4.2 Full-state feedback with added integral control

The data flow diagram from this system, figure 5.9, again reflects the control block diagram derived in chapter 2, see figure 2.13. The addition of the integral term and its associated calculations still allow the system to be configured as shown in figure 5.10. The extra terms associated with the integration increase the execution time of the controller calculation by 10 μs. This is still within the system specification. Experimental

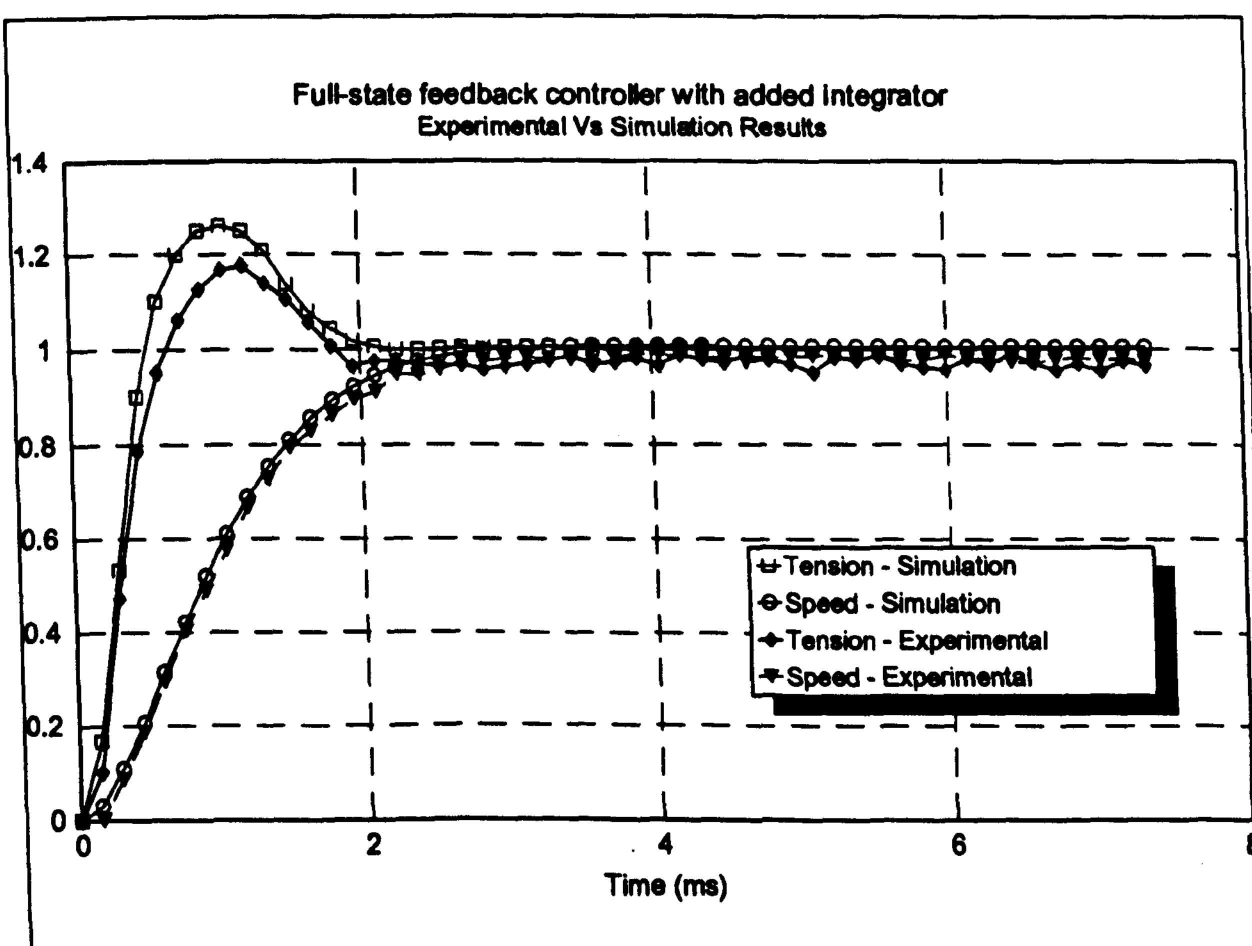

Figure 5.8 - Unit step response for tension/speed

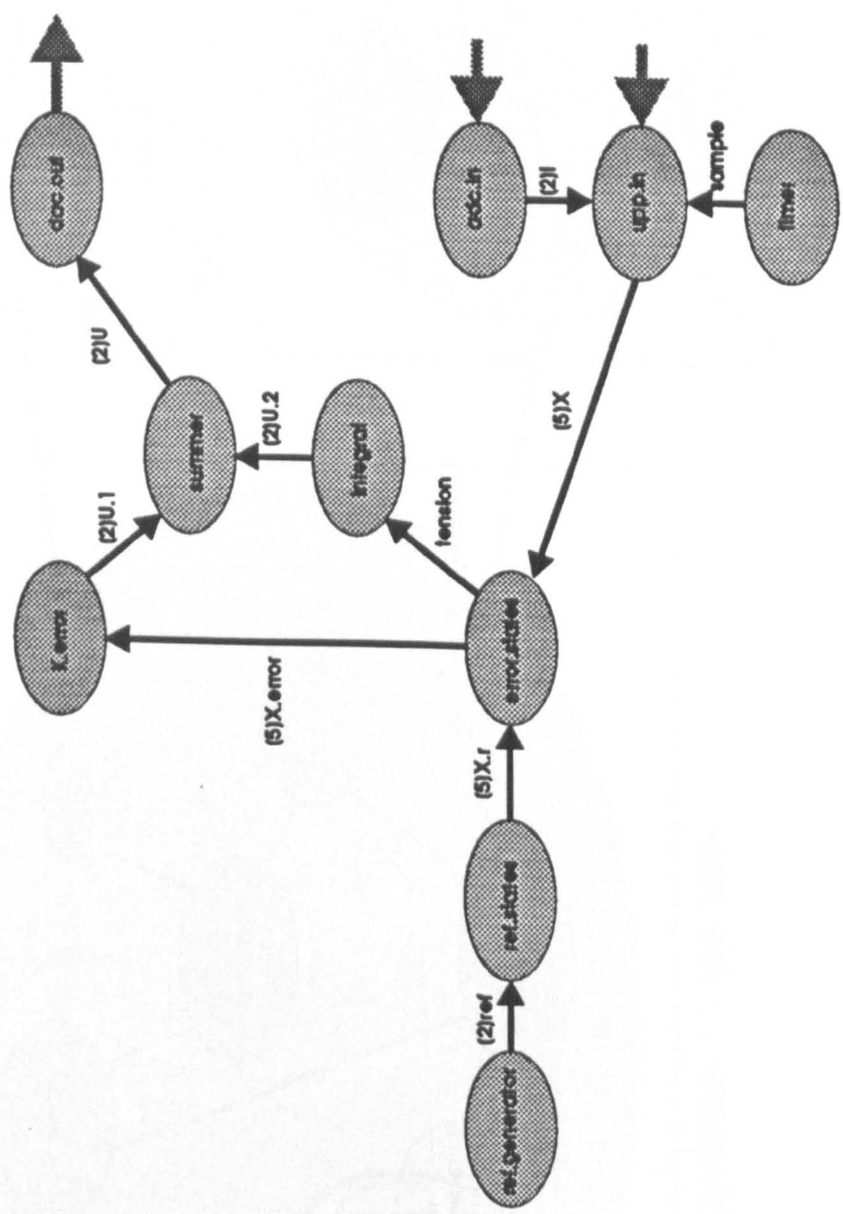

Figure 5.9 - Process + data flow configuration
full-state feedback with added Integrator.

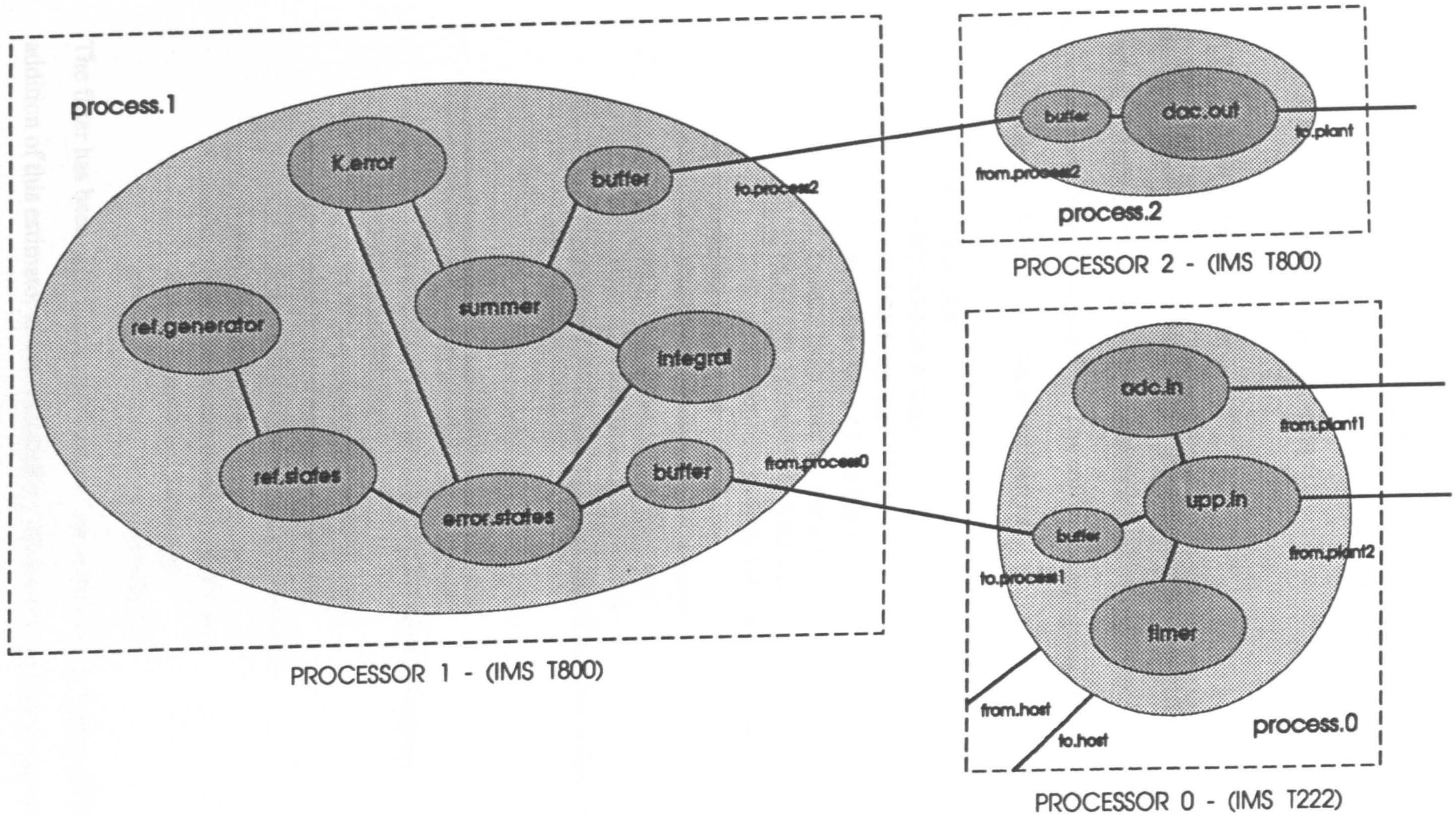

Figure 5.10 - Processor configuration full-state feedback with added integrator

and simulation data for the system response tests are shown in figure 5.8. The steady-state error of the tension present in the full-state feedback controller configuration has been eliminated. The experimental tension response tests show a reduced peak overshoot. This discrepancy is due to slightly differing properties of polyester film between manufacture. However it illustrates that the system can cope with these parameter changes to give responses within the system specification.

5.4.3 Kalman filter estimator

The introduction of the Kalman filter to the system was intended to eliminate most of the external disturbance seen in the previous two controllers. The process and data flow for this system are shown in figure 5.11. The software configuration to implement the system shown in figure 5.12 and 5.13 can be written as,

```
PLACED PAR
  PROCESSOR 0 T222
    PLACE from.host AT link0.in:
    PLACE to.host AT link0.out:
    PLACE from.plant AT link3.in:
    PLACE to.process1 AT link2.out:
    process.0(from.host,to.host,from.plant,to.plant)
  PROCESSOR 1 T8
    PLACE from.process0 AT link0.in:
    PLACE to.process2 AT link2.out:
    PLACE from.process3 AT link1.in:
    process.1(from.process0,to.process2,from.process3)
  PROCESSOR 2 T8
    PLACE from.process1 AT link0.in:
    PLACE to.process.3 AT link2.out:
    PLACE to.process4 AT link1.out:
    process.2(from.process1,to.process3,to.process4)
  PROCESSOR 3 T8
    PLACE from.process2 AT link1.in:
    PLACE to.process1 AT link0.out:
    process.3(from.process2,to.process1)
  PROCESSOR 4 T8
    PLACE from.process2 AT link0.in:
    PLACE to.plant AT link1.out:
    process.4(from.process2,to.plant)
```

The filter has been split into two processes, measurement and time update processes. The addition of this estimator and its associated calculations gave unacceptable computational times with the configuration used in the previous two control designs. A benchmark of the

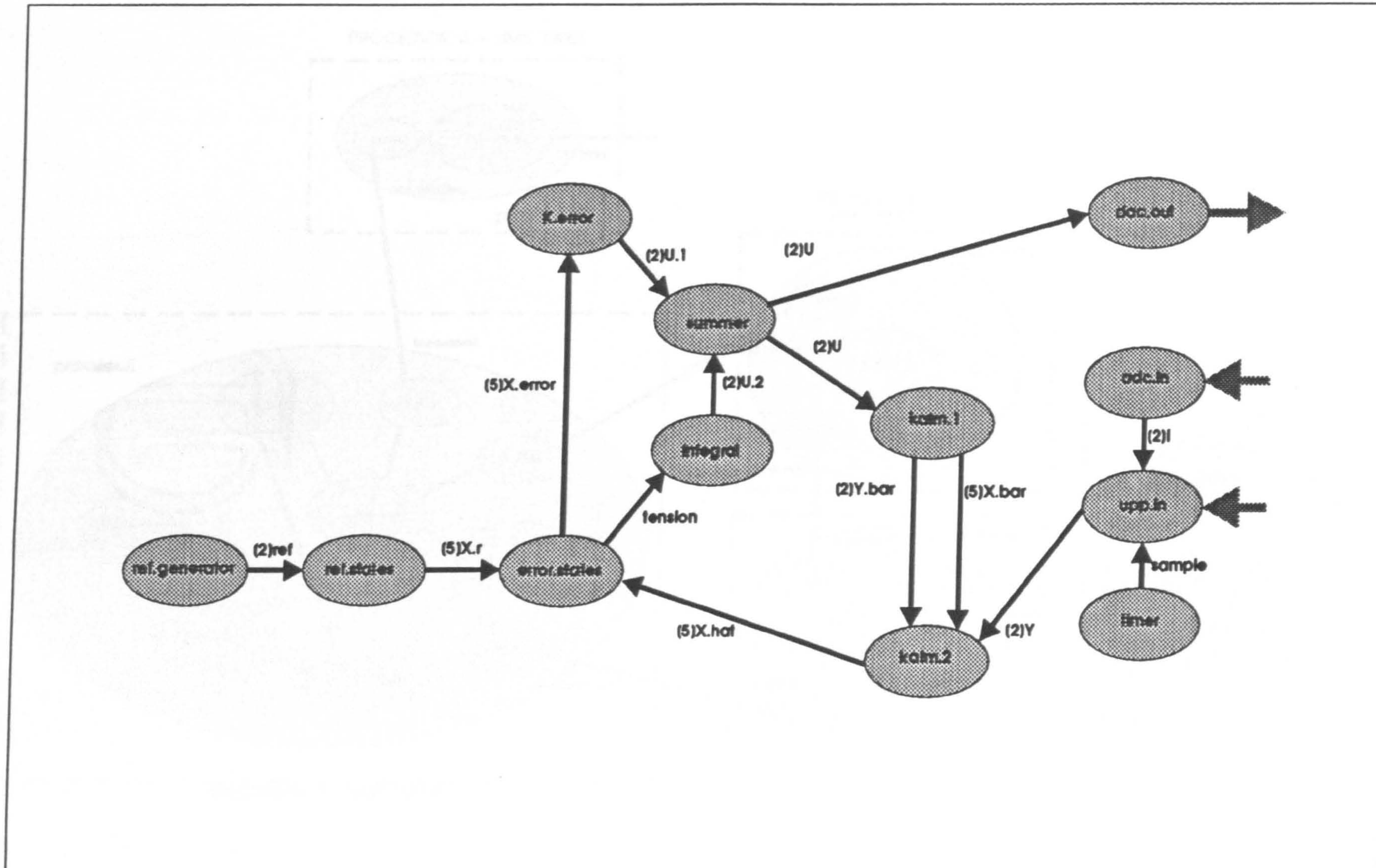

Figure 5.11 - Process + data flow configuration

Full-state feedback + integrator + estimator.

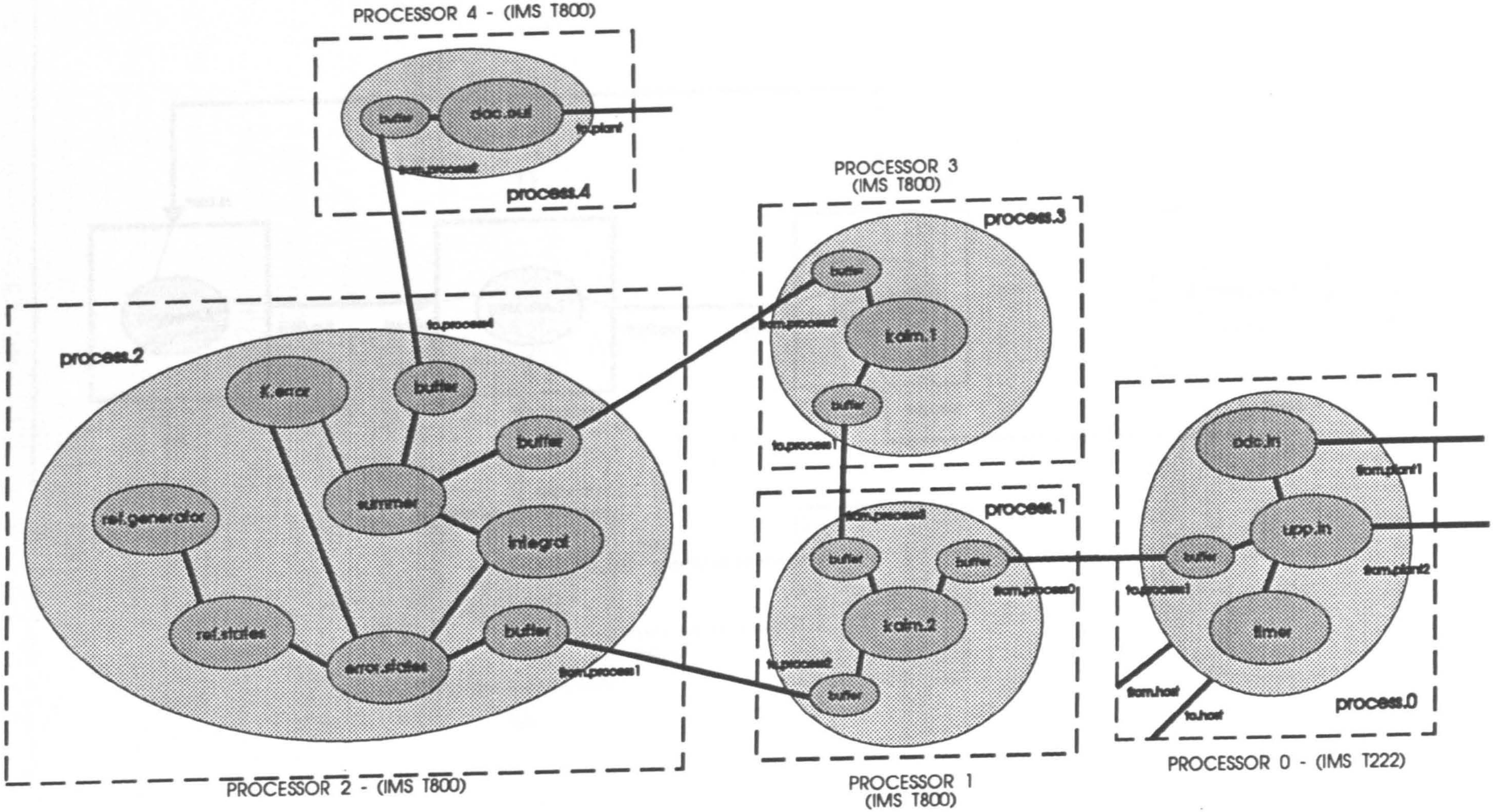

Figure 5.12 - Processor configuration
full-state feedback + integrator + estimator.

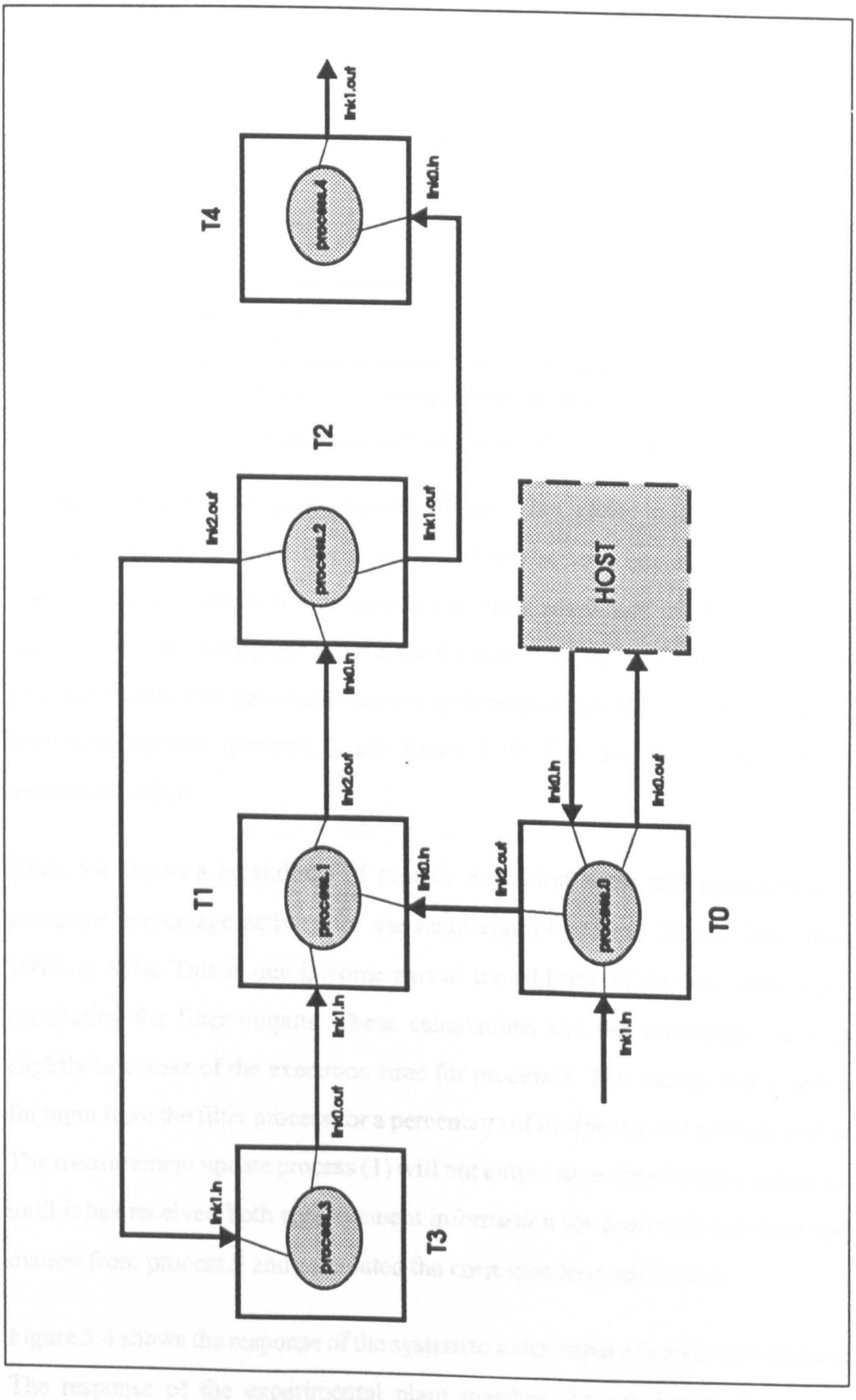

Figure 5.13 - Transputer hardware configuration
Full-state feedback + Integrator + estimator.

n	Processor *n* % Activity	Process.*n* Execution Time (μs)
0	15%	20
1	87%	40
2	85%	80
3	65%	30
4	20%	20
Total Execution Time μs	160	

Table 5.4 - Controller performance figures

Full-state feedback + integrator + estimator

Kalman filter on its own gave a figure of 70 μs. This, added to the 115 μs of the full state feedback system, reduced the accuracy of the system beyond the specification. To overcome this problem it was decided to take advantage of the parallel processing capabilities of the transputer and run the Kalman filter on two individual processors. One processor would calculate measurement updates (process.1), the other would calculate the filter time updates (process.3), see figure 5.12. The overall computational time was reduced to 160 μs.

Table 5.4 shows a breakdown of process execution times and processor activity. The processor percentage activity for the main control process (2) has been reduced from 100% to 85%. This is due in some part to the addition of the two additional processes calculating the filter outputs. These calculations and the subsequent data transfer are slightly in excess of the execution time for process.2. This means that it will be waiting for input from the filter process for a percentage of its time i.e. the process will be inactive. The measurement update process (1) will not output its estimated state values to process.2 until it has received both measurement information for process.0 and time update information from process.3 and calculated the corresponding state value.

Figure 5.4 shows the response of the system to a step input of speed and tension command. The response of the experimental plant matches the simulation almost exactly. The reduced order model used in the simulation tests tended to be less robust than the actual

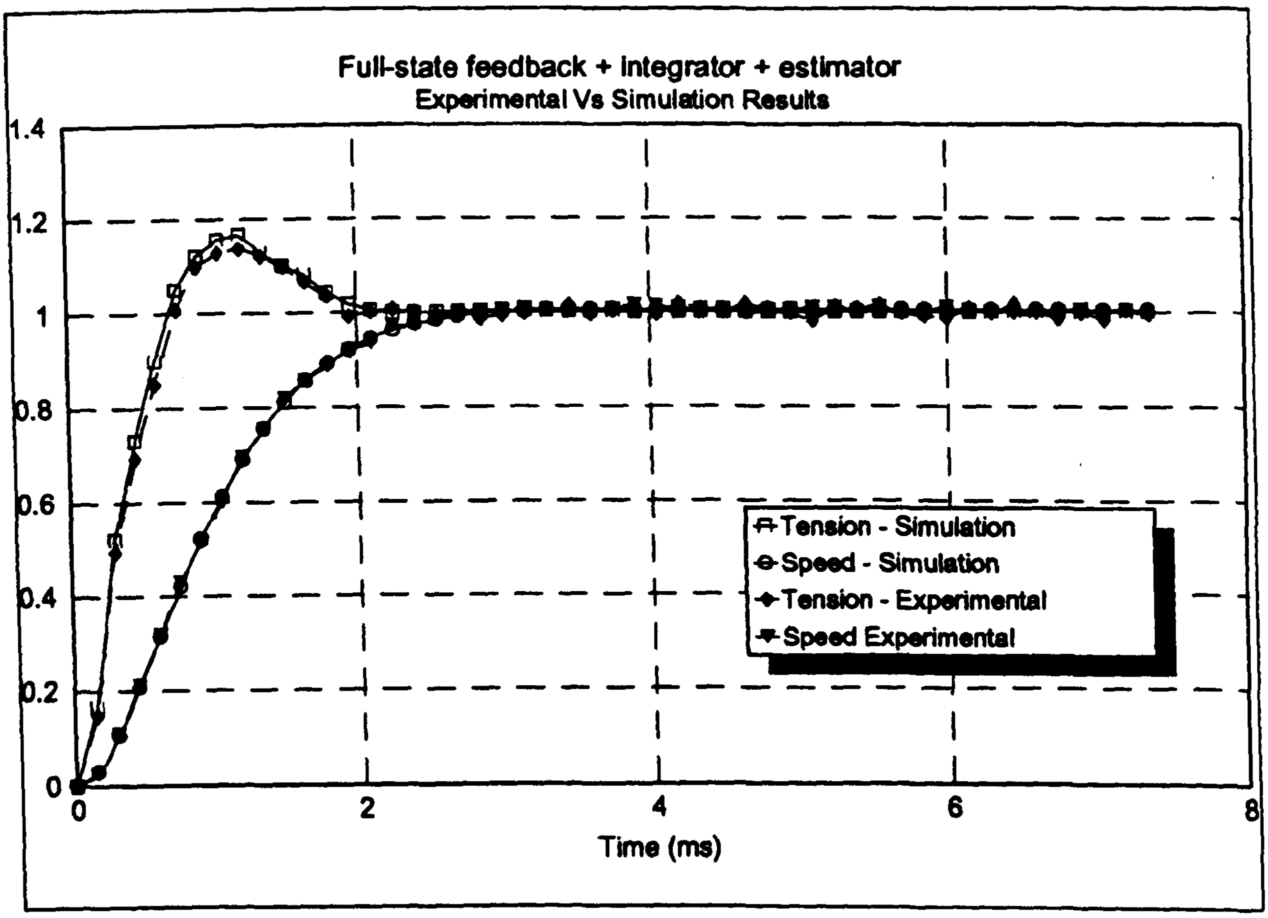

Figure 5.14 - Unit step response for tension/speed

plant, typically to the response from external disturbances and sensor noise. The experimental rig used to test the control algorithms showed better than expected results in terms of damping out any unwanted tension fluctuations. The servo controller used also contained unknown parameters such as signal conditioners and filter circuitry. A more detailed examination of the servo controller could be undertaken to gain a better model i.e. frequency response testing under differing motor load/speed conditions.

Summary

The system design was based around a modular format of servo drives and TRAMS. This use of modules allowed for quick development and testing of individual components of the system and flexibility for testing different control strategies. For maximum flow of input and output control and feedback data, memory mapped devices were used. The servo drive system was used used in torque mode to provide the motors with a drive signal proportional to torque output. This torque mode eliminated the effect of motor inductance so increasing the system bandwidth. Film speed measurement was taken directly from the surface of the film by measuring the direct speed of the capstan drives. Tension measurement was proportional to the difference in the torque delivered to each motor and was obtained directly from the servo amplifier control signal.

The control algorithms developed in chapter 4 were implemented on the transputer. Full-state feedback, integral and estimator control were used on different transputer configurations. Performance figures for each control strategy were obtained in terms of execution time and system response. Mechanical imperfections in the system could be compensated for, up to a point, by 'tweaking' the control algorithm gains. This was most evident in the implementation of the estimator. The experimental plant was found to be more robust than the simulation. This was found to be due to good mechanical damping of the system, reducing effects from tension fluctuations and characteristics of the electronics, not used in the modelling process.

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Chapter 6

Conclusions

The capstan drive system developed in this research project has shown that the concept of 'spocketless' film transport for printing is wholly feasible. Until now the lack of affordable high speed computing devices has been the limitation in implementing currently available control methodologies.

The conclusions can be divided into three main areas. These main areas engender the logical sequence of this research project.

6.1 Development of Capstan Drive System.

The work undertaken in this project has been developed from a study undertaken of the industrially based method of the motion picture printing and copying process. The study reviewed several areas of picture unsteadiness.

Multiple final show prints are produced from a single copy negative. The film transport mechanism, sprockets, has the unavoidable effect of wear on the film perforations. The wear caused by the sprocket based transport mechanism ultimately reduces the high tolerance that the film perforations are manufactured to, (0.00254mm). As these discrete perforations are the only reliable source of location for the registering of film, movement of film will occur giving rise to unacceptable picture unsteadiness. The current drive transmission of sprocket based printing machines consists typically of a single DC servo motor connected to all the intermediate drive sprockets and main drive sprocket through a series of gears and timing belts. This single drive motor is controlled by a single velocity controller. There is no direct measurement of film speed or film tension.

Other factors that can exaggerate picture unsteadiness are: a build up of dirt on the sprocket teeth or film transport rollers, mis-alignment of transport rollers and guide rollers in the area of the printing head, and mechanical drive transmission problems.

The study revealed a need to replace the sprocket based film transport mechanism with one that could not only improve the printing speed of the film copying process, currently 2.5 - 3.0 m/s, but also eliminate the current problems of film unsteadiness.

The studies conducted during this research project of current film transport mechanisms and analogous systems such as video and audio, have led to the development of a capstan drive based film transport system. The capstan based transport system has followed the new trend of mechatronics, that is replacing most or all of the mechanical gearing systems and timing pulleys by software processes.

The new motion picture film transport system has a more direct control of film speed and unlike conventional systems has a dynamic tension control mechanism to eliminate external tension disturbances which have been shown to be the main cause of picture unsteadiness. These new capabilities have been achieved through independent drive motors connected together by software based control algorithms, direct film surface speed measurements, estimated tension measurement eliminating the need for tensioning arms, and fast processing of the control algorithms.

6.2 Simulation and Control System Design.

The design of a suitable controller was formulated from the state-space description of the capstan drive. This state-space description was formed by linearising the equations of motion of the various components of the plant. This description was used to develop controller strategies based on linear quadratic regulator and state-feedback methodologies. A full-state feedback controller was initially designed and tested on the plant model. From the results it was shown that the tension output of the system was the main factor contributing to the film transport unsteadiness. The addition of external tension disturbances gave a steady state error on the tension term of 10-15%. The control of the film dynamics was significant in achieving the system specification. The reduction of this steady state error for the tension output was achieved by adding an integrator term to this control variable. The speed response of the system to a unit step disturbance was 3 ms throughout the design of the controller, this was shown to be partly due to the mechanical damping of the system and the excellent decoupling of the two drives by the regulator gain matrix. To further reduce the effects of external disturbance and steady-state error an estimator was designed. This estimator was based on the Kalman filter and the resulting gain matrices were based upon the steady-state operating conditions of the plant. The estimator gave the system excellent rejection to tension disturbances and process noise. Small discrepancies between experimental and simulated results were due to measurement of the current. This was alleviated when the Kalman filter was incorporated.

The two motors that made up the capstan drive were configured for torque control which essentially meant that the control effort was directly proportional to the current signal. The system response results showed that the speed of the film is directly proportional to the difference in current signal while the tension in the film is directly proportional to the sum of the current signal.

6.3 Transputer Implementation.

The transputer can be thought of as a tool for the implementation of developed control algorithms. It is a flexible device and allows quick and efficient prototyping of system. The use of the transputer's generic programming language, Occam, has been shown to allow the development of small procedures of code describing directly each element of the controller. A direct mapping from the control block diagram description of the controller to a process and data flow description of the control algorithm is shown. This process description can be coded as discrete processes connected together by links. Initially these links are described in the abstract (software links) so the controller can be tested on a single transputer. From the process and data flow description potential signal flow bottlenecks were identified. From benchmark timing results computational elements of the controller were identified. The main controller process consisting of the LQR gain and the integrator took 80 μs to execute keeping the processor busy 100% of the time. Each input and output process was placed onto a separate processor and ran in under 20 μs. These results allowed the controller to be mapped onto multiple processors to achieve the required sample time of 150 μs. The Kalman filter was divided amongst two processors with the main control algorithm again executing on a single processor. Buffer processes were used to buffer each link from the main control process. The execution time of the controller with estimator was 160 μs. Potential problems were identified as the current limitation of the number of transputer links (4) and the limitation of hardware devices for data input-output.

Summary

The following have been achieved.

i) Capstan drive avoiding toothed drive avoiding perforation wear.

ii) Complete and adequate simulations of the capstan drive system.

iii) Design of modern controller using state feedback with integral and estimator terms.

iv) Implementation of these controllers on a transputer network.

v) Construction of prototype rig.

vi) Validation of simulation with good accuracy on test rig.

Chapter 7

Future Work

The work carried out in this project can be applied to many applications of mechatronics both in the film industry and in other areas.

The capstan drive system developed in this project has been designed to transport a single length of film. A full printing system would use two identical transport control systems, one for the copy negative and one for the positive stock. Using the same procedures undertaken in this study a single control system could be designed to combine both films. At present the desired output for each strand of film are speed and tension. The aim is to reduce film unsteadiness. This film unsteadiness could be measured by using a non-contact sensor which utilises the film perforations as a direct measurement of film speed/position. The unsteadiness value could be considered as a measurable output state. The system could utilise phase-lock loop techniques to ensure constant film speed and could be considered as a 'software' sprocket drive.

The film transport system is only one area of the printing machine. Other areas that could benefit from work undertaken in this research are film winding system, light valve control systems and fader control. Ultimately it is envisaged that a single multi-processor system (or equivalent) could control all the operations on the printing machine.

7.1 Winding Processes

Many industrial applications that deal with the manufacture and transport of warp material rely on winding mechanisms to feed or take-up the material.

7.1.1 Film Winding

Continuous contact printing of 35mm motion picture film as covered in this project is achieved by passing a picture negative film with raw film stock (positive) over a printing aperture. The intermediate drive system maintains constant velocity of each piece of film as well as a constant running tension. Each piece of film has associated with it a take-up and feed reel. These must feed and take-up from the intermediate drive system without affecting its performance, this could result in movement between positive and negative film so resulting in picture image unsteadiness. The complex motion profiles involved with winding film which is a inherently non-linear system to control lends itself to the use of robust controllers such as the ones developed in this project. Other control techniques could also be applied such as gain scheduling (based on the film reel radius), and model following techniques.

7.1.2 Filament Winding

The winding of filaments is used in many industrial situations. Two main areas are the coil winding applications of electrical equipment including solenoids, motor windings and transformer coils, and for use in filament winding during fabrication of fibre-reinforced composites.

The winding of coils has been made far easier with the advent of CNC type machines. These type of machines employ modern servo techniques that can accurately control speed, tension and accelerations of the winding operation. Unlike film winding there is an extra lateral axis. This dual motor winding arrangement requires sophisticated computer software and hardware such as developed in this project. Filament winding has been used for many years to produce high-performance, low-cost components such as rocket-motor pressure vessels, launch tubes, and structural components; chemical tanks, aircraft components, helicopter blades.

A typical application of these filament winding machines is to lay a resin impregnated band of fibre glass or other reinforcing material on the surface of the mandrel in a precise geometric pattern. The advent of microprocessor control has been used to produce complex geometry of winding patterns used in some applications for added strength and support. Microprocessor control has also made it possible to program simple geometries such as constant helical winding and to sequence wind programs automatically.

7.1.3 Warp Winding

This area of winding resembles the winding of film but on a far greater scale. Typical areas of warp winding are in the yarn and paper industry.

In the area of warp winding, problems can arise in the weaving of the cloth and the maintenance of the correct tension. As in all winding processes, as the yarn leaves the reel (beam), the effective radius of the beam slowly decreases. To maintain a uniform rate of feed, the angular velocity of the beam must increase. To ensure a constant good weave the tension of the yarn must be maintained at all times.

The paper industry has a very similar problem in maintaining correct tension. Both processes overcome these problem by use of correctly designed tension arms although the type of servo controller is usually very basic. More sophisticated controllers based on those investigated in this project could be utilised to improve both the quality and quantity of paper.

In the paper industry, specifically the production of newsprint, the transport of the paper at the correct speed is very important. Capstan pinch rollers are usually used to ensure that the correct speed is maintained. In some systems the control system that monitors this speed is also used to control the winding stations. This type of application lends itself to the capability of a multi-processor-processor system or distributed system controlling several parts of the same operation using generated control information from one controller to control the operation of another.

7.2 Processing Power

The use of the transputer has been used for its inherent flexibility and usefulness in quick system configuration from control algorithm description. Could this computing 'tool' be replaced with other computing platforms ? The limitations of the current transputer (4 links) could be solved in the near future with the pending launch of a new transputer computing device (IMS T9000) that supports virtual links i.e. memory mapped. Implementation of the control algorithms on this faster and more flexible computing device might further improve system performance until the only limitation on the speed and accuracy of film printing is the physical constraints of the hardware.

The controller design covered in this work has considered one type of design methodology. The prototype system is now available for further work in this area. Work has been initiated using Doyle's Robustness techniques and μ controllers. Such controllers could utilise the improved processing power of newer devices such as the IMS T9000, Intel's i860 and the C40 processor developed by Texas instruments.

7.3 Non-symbolic based controllers.

Present controllers are based on known design methodologies that formulate strategies based on the desired system response. Work on control algorithms that involve the development of artificial intelligence based controllers such as those based on artificial neural network systems is currently being investigated. The neural controller is a network of weighted interconnections that has previously been 'trained' in response to a set responses. These responses or training sets could be derived from 'real' experimental data or from simulation data. The training sets would consist of known inputs to the system and corresponding 'desired' outputs. For example, a step input to the system should produce a response to satisfy the system specification, if not the weighting's of the network interconnections are changed, according to some algorithm, until the error at the output, actual output compared to desired output, is less than some pre-defined tolerance.

Once the network has been trained it can be used in place of the conventional controller. One advantage of artificial neural networks over conventional systems is that they can extract data from noisy or incomplete signals such as those from sensors.

The system designer has now all the tools necessary to develop more and more sophisticated devices using the mechatronic design approach. Using modular design techniques the flexibility of such systems is limited only by the ingenuity of the engineer. Modularity has allowed integration of dedicated processors for specific purposes from computation of complex control algorithms and motion profiles to the integration of processors with sensors for added 'intelligence'.

Appendix A

Film Printing Methods

A.1 General Uses of Type C Printers

Type C printers (Model 'C') are flexible machines which can be used for a wide variety of tasks. Unlike the panel printers they can only copy in one direction and therefore they are not particually suited to bulk production copying. However with their fader capabilities they can be used to produce sophisticated effects in negatives which can then be used for bulk copying on panel printers which do not have faders.

A.2 A and B Printing

Figure A.1 shows the principles of A & B printing. In this method two originals are used, each contain alternative scenes separated by blank film. In the example of figure A.1 the A negative contains scenes 1 and 3, the B negative contains scenes 2 and 4.

On the first print run the contents of A are transferred to the copy stock. In the example shown 2 dissolves are produced at the end of scenes 1 and 3. A sharp cut scene change is produced at the beginning of scene 3.

On the second print run the contents of negative B are superimposed on the copy stock which now contains the scenes from A. This time scenes 2 and 4 are 'faded in' to match the 'faded out' scenes 1 and 3. The sharp cut-off scene change at the end of scene 2 is synchronised to the start of scene 3.

These features call for an accurate control of faders and light valves to particular frame lines.

A.3 Wet Printing

Some type C printers are adapted to copy from badly scratched originals. This is achieved by wet printing. For slightly damaged originals a spray head is used to wet the back of the

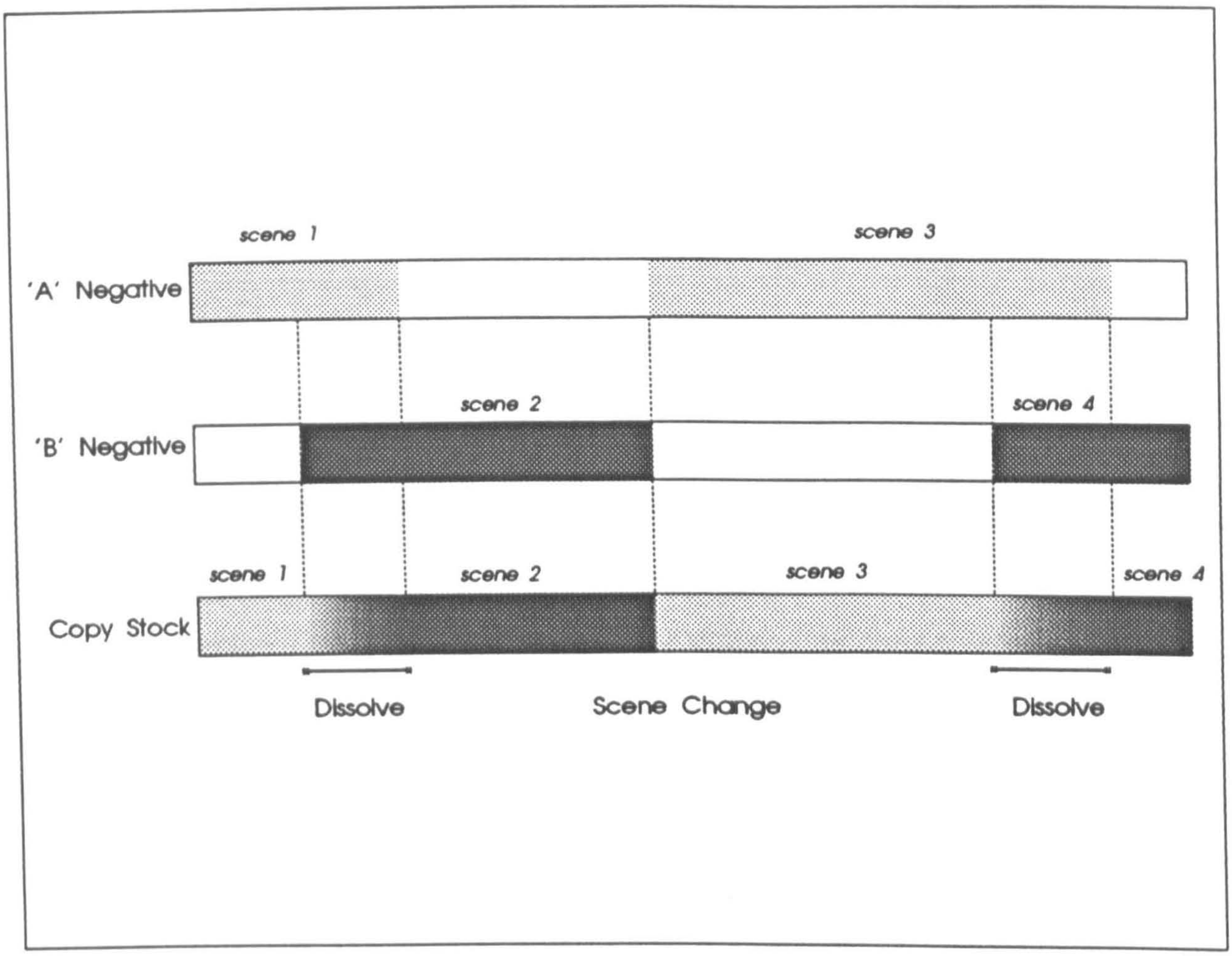


Figure A.1 - A,B Printing

film. The liquid used has the same optical refractive index as the film which has the effect of making the scratches optically invisible.

For greater damage total immersion is used in which the film is copied under the surface of a bath of liquid. In both spray and total immersion printing the film has to be dried before it is rewound.

Appendix B

Determination of Film Properties

In order to understand and study the dynamics of motion picture film in those processes involving high-speed transport such as in bulk contact printing, it is necessary to obtain values for the stiffness (k) and damping coefficients (c) of the film. To maintain a constant speed, feedback data such as tension, velocity and position of the film are used in a control system. To design such a system it is essential to have the correct information on the dynamic properties of film transport.

Measurement of these properties using the following procedure was carried out on various lengths of 35mm motion picture film. The lengths of film were used in a single degree of freedom mass(m)-spring-damper system with the film acting as the spring damper element.

The equation of motion of the mass is found by using Newtons Second Law,

$$m\,\ddot{x}(t) + c\,\dot{x}(t) + k\,x(t) = f(t) \tag{B.1}$$

Where

$f(t)$ = applied force

$x(t)$ = resultant displacement

$\dot{x}(t)$ = resultant velocity

$\ddot{x}(t)$ = resultant acceleration

The film sample to be tested was fixed in a clamp at the upper end whilst the other end was used to support a known free hanging mass.

Two accelerometers were used, one as a counter balance weight. A force transducer was attached to the mass in such a way as to allow force inputs to the centre line of the film to be measured. The system was forced by random signals originating in the dual channel signal analyser and amplified before driving an electromagnetic shaker which was connected via a push rod, effectively a mechanical fuse, to the force transducer connected to the mass supported by the film. The ratio of the $\frac{\text{accelartion}}{\text{force}}$ (inertance) resulting from duel spectrum averaging measurements was displayed as Bode and Nyquist plots. Response data was captured by the analyser and subsequently recorded on a pen plotter.

The transducers were calibrated against a known mass in a preliminary exercise to obtain a Inertance Scale Factor. A wide band scan showed that the frequency range 15 to 40 Hz. was of most interest since it contained the system resonance and detailed testing was restricted to this range.

Once a resonant peak had been obtained a suitable input signal to the shaker could be calculated so as not to allow the film to lose tension during testing.

The amplitude of resonance was found by measuring the accelerometer response to a sinusoidal signal at the resonant frequency of the system. The calibrated accelerometer signal was integrated twice to obtain a value for maximum displacement. This then allowed tests to be carried out at different amplitudes so as to explore any amplitude non-linearities.

From the magnitude response of frequency a measurement of the 3 dB bandwidth about the resonant peak was made, see figure A.2. The value of the resonant frequency could then be used to determine the stiffness of the system and the 3 dB bandwidth used to obtain the damping of the system. Using the signal analyser it was found that the results were subject to a tolerance of +/- 5%.

B.1 Results

From the table of results, table A.1, it can be seen that there are distinct differences between tri-acetate film and polyester based films with lso a marked difference within these categories of the make of film used. it should however be noticed that the percentage difference in the stiffness properties of each type of film vary by 12% while the damping properties for each type of film base vary by 63%.

Film Type/Make	Kodak 5384	Fuji 8816	Kodak 5243	Agfa
	Tri-acetate		Polyester	
Young's Modulus - N/mm^2	3500	3880	4010	4000
Damping Ratio	0.025	0.024	0.0083	0.0087
Stiffness Coefficient - N/m	18400	20300	21100	21000
Damping Coefficient - N/(m/s)	14.0	13.8	4.9	5.1

Table B.1 - Properties of 35mm motion picture film

This variation in film property must therefore be taken into account when designing a suitable film transport control system. The transient response of polyester film to a step input (e.g. speed) will be different to that of tri-acetate film in the sense that the time for the polyester film to reach steady-state will be longer than that for acetate.

Because different types (and makes) of film are used in the film industry a accurate transport control system will have to be robust, i.e. for a change in plant gain due parameter change (film properties) the system will still have a zero steady state gain to a constant input.

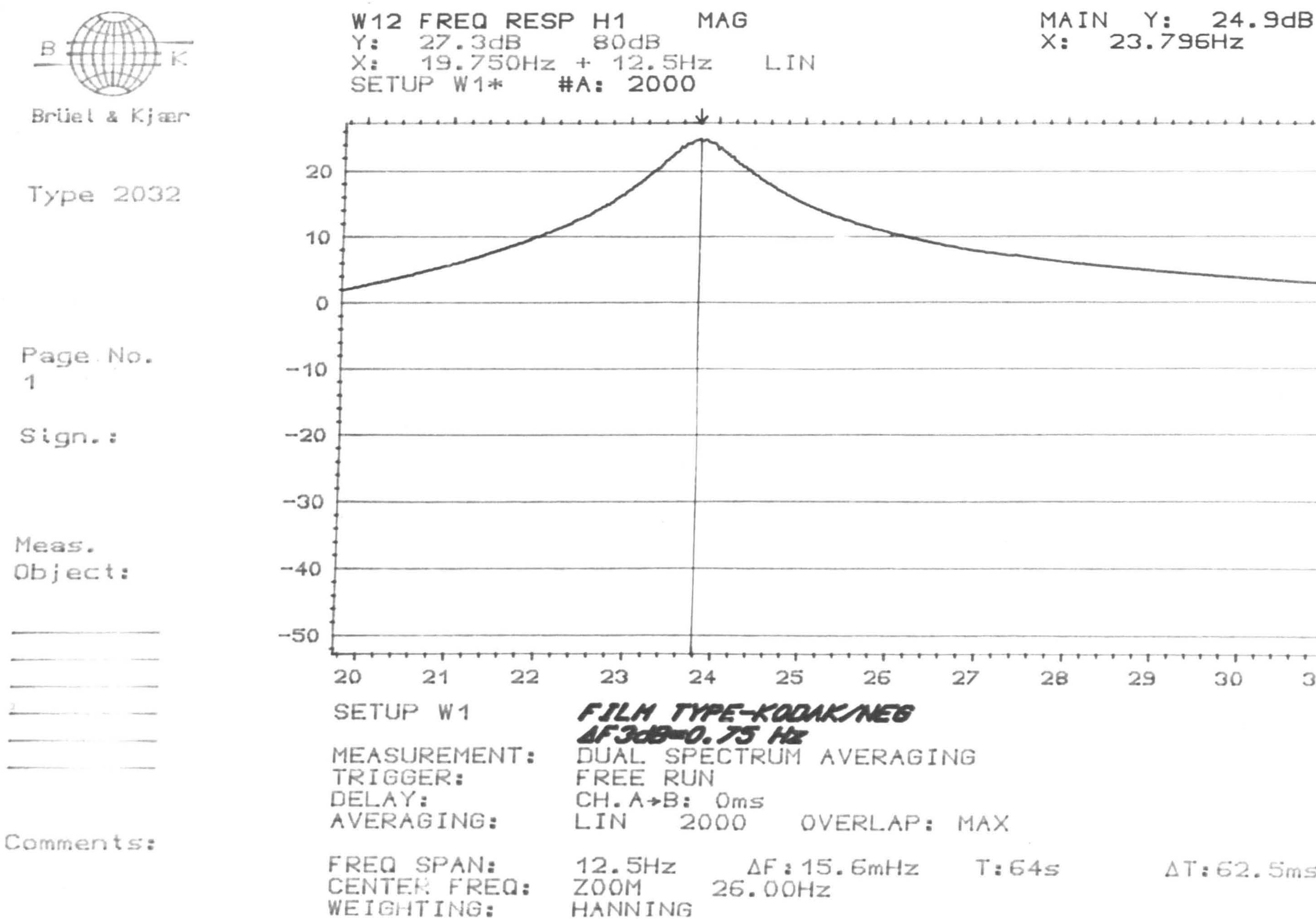


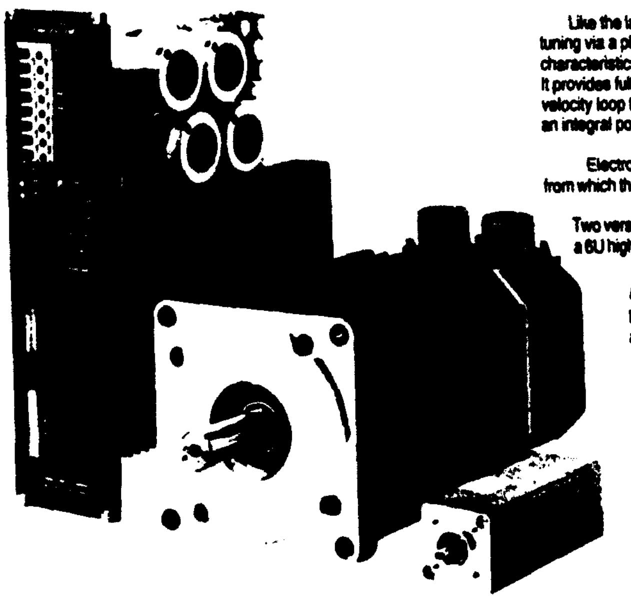
Figure B.1 - Frequency response (magnitude) -35mm film

Appendix C

Published Papers

Appendix D

Technical Data Sheets



The BRU-100 is a competitively priced, high performance drive that makes brushless systems a real financially viable option for the small servo motor application. It is a complete single axis analogue amplifier designed for use with standard three-phase trapezoidal motors from 0.14Nm to 10Nm cont. (0.8Nm to 22Nm pk.).

Like the larger units in the family of BRU drives, the BRU-100 offers initial tuning via a plug-in personality module which matches drive and motor characteristics, and can be fitted to replacement drives to eliminate retuning. It provides full four quadrant torque or velocity control, and an encoder velocity loop that eliminates the need for a tachometer. In addition it features an integral power supply and bus dump.

Electro-Craft's PRO positioners are fully compatible with the BRU-100, from which they can source power and will rack-mount alongside.

Two versions are available - 15A/8A and 30A/15A - and both are configured on a 6U high extended Eurocard.

DRIVE MODULE *(with built in power supply)*

Performance with 32kHz ripple frequency and 20-0-20VAC (AM15) and 40-0-40VAC (AM30) nominal input voltage.

Drive Module Type		AM15	AM30
Peak output current/phase	A	15	30
Continuous output current/phase	A	6	10 (15*)
Continuous output power	kW	0.24	1.2

**Fan-cooled - 24 VDC power connector provided.*

Electrical Characteristics			
Input signal range	± 10 V DC (20 V DC maximum)		
Input impedance	20 kOhm		
RMS line voltage input single phase 50/60Hz	VAC	20-0-20	40-0-40
Continuous shunt power	W	20	40
Peak shunt power (50mSec)	W	800	1600

Physical Characteristics			
Operating temperature	0 to 40°C		
Storage/shipping temperature	−40 to 80°C		
Relative humidity	5 to 95%, noncondensing		
Weight	kg	1.3	2.1

SYSTEM RATINGS WITH BRU-100 STANDARD MOTORS (Temp. Rise 85°C)§

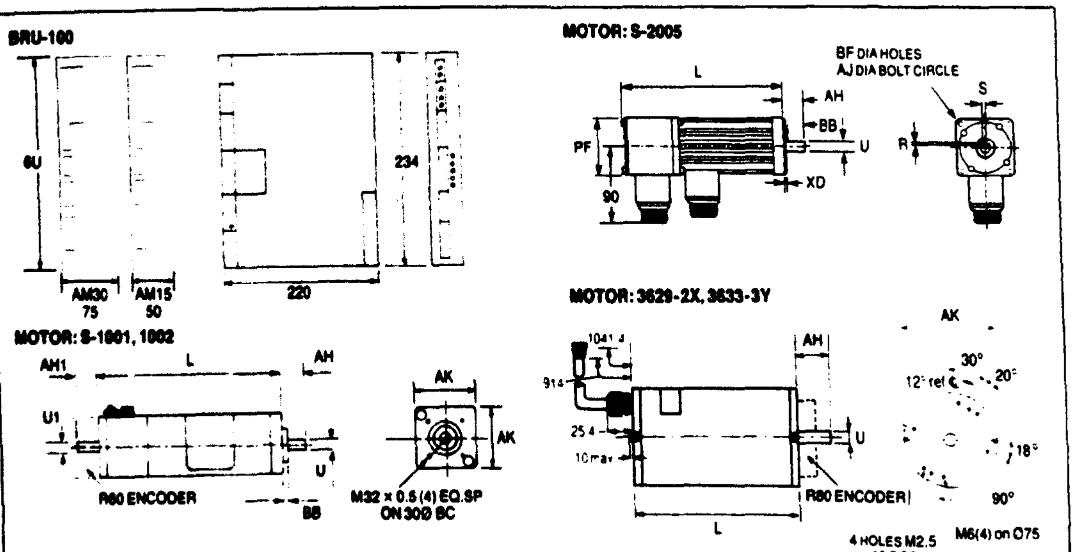
Drive module type (32 kHz ripple frequency)		AM15/30	AM15/30	AM30	AM30	AM30	AM30	AM15	AM30
Motor Type		S-1001	S-1002	S-2006	S-3016	S-4050	S-4075	3629-2X	3633-3Y
Continuous stall torque	Nm	0.14	0.25	0.56	2.2	6.8	10	0.7	1.5
Peak torque	Nm	[illegible]	[illegible]	2.1	8.5	15	22	1.7	6.2

STANDARD BRU-100 MOTOR SERIES

Motor Type		S-1001	S-1002	S-2006	S-3016	S-4050	S-4075	3629-2X	3633-3Y
Rotor moment of inertia	$kg\,m^2$	$1.3 \times 10^{[illegible]}$	$2.5 \times 10^{[illegible]}$	15×10^{-6}	$8 \times 10^{[illegible]}$	4.6×10^{-4}	6.8×10^{-4}	1.2×10^{-4}	$3.18 \times 10^{[illegible]}$
Maximum continuous operating speed	rpm	7000	10000	6000	3000	1700	1100	4000	4000
Motor weight, including feedback	kg	0.5	0.7	2.3	3.3	10	13	2.6	4.5
Winding data	Designator	-	-	K	N	P	R	X	Y
K_t torque constant	Nm/A	0.07	0.07	0.14	0.28	0.50	0.72	0.11	0.23
K_e voltage constant	V/k rpm	8	8	17	34	60	88	12	24
Winding resistance, phase to phase @ 25°C	Ω	5.7	2.5	2.6	1.3	0.8	0.8	3.8	5.0
Winding inductance	mH	4.5	1.7	4.3	3.7	3.9	5.8	1.8	3.4
Thermal resistance	°C/W	3.4	2.6	1.45	0.89	0.57	0.48	2.2	1.5
Radial load 12.7mm from shaft end	kg	5	5	10	15	20	20	6.8	9
Axial load	kg	2	2	5	5	10	10	3	3

§40°C ambient temperature.

S series motors are supplied without keys.



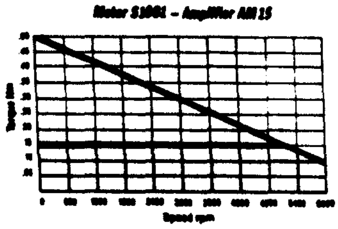
See BRU-500 and BRU-200 for S-3016, S-4050 and S-4075 dimensions

Model	AJ	AK	P	PF	U	U1	AH	AH1	BB	BF	XD	S x R	L
S-1001	-	38.1	-	-	6h6	5	15	10.4	3.175	-	-	-	92.8
S-1002	-	38.1	-	-	6h6	5	15	10.4	3.175	-	-	-	114.0
S-2005	75	-	-	63.5	11h6	-	23	-	2.4	5.8	18	4 x 2.5	185
3629-2X	-	86.9	-	-	12h6	4.8	50	10.3	-	-	-	-	130.5
3633-3Y	-	98	-	-	12h6	4.8	50	10.3	-	-	-	-	166.0

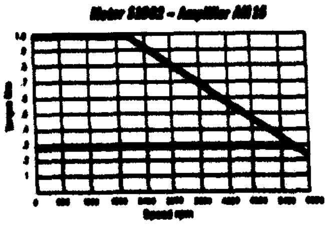
SYSTEM PERFORMANCE

☐ Continuous Operating Region ☐ Intermittent Operating Region

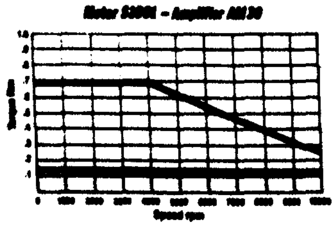
Motor S1001 – Amplifier AM15



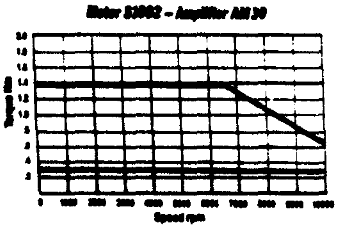
Motor S1002 – Amplifier AM15



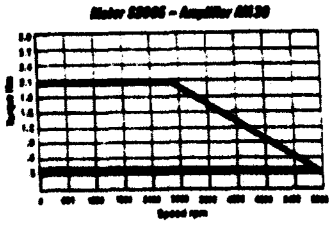
Motor S1001 – Amplifier AM30



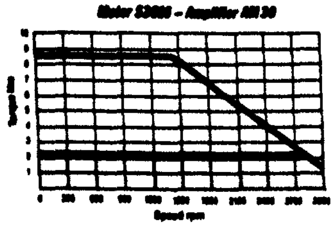
Motor S1002 – Amplifier AM30



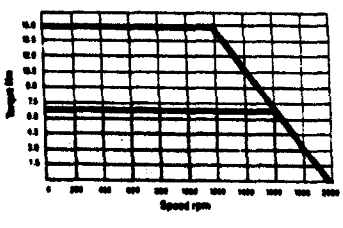
Motor S2005 – Amplifier AM30



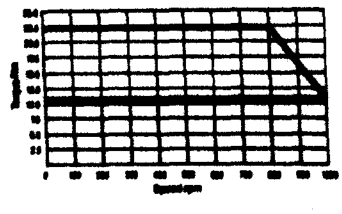
Motor S3016 – Amplifier AM30



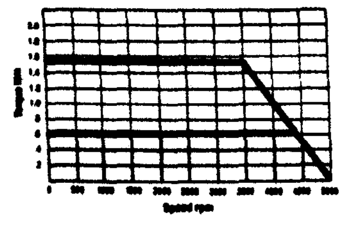
Motor S4050 – Amplifier AM30



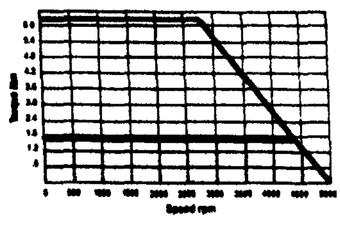
Motor S4075 – Amplifier AM30



Motor 3629-2X – Amplifier AM15



Motor 3633-3Y – Amplifier AM30



MODEL R60 SERIES
MODULAR ENCODER

The R60 Series is a low cost, 1.5 inch diameter, high performance kit encoder featuring an LED light source, and Radial-Line Sensor Array which minimizes interchannel jitter and amplitude modulation found in other kit encoders. The sensor array, LED, and mask are prealigned during manufacture to eliminate costly setup procedures and the need for special alignment tools.

The R60 is an easy to install kit consisting of a photohead assembly, hub/disk assembly, dust cover and mounting hardware with instructions.

The R60 is available with standard output configurations including a once per revolution index pulse and resolution to 1875 lines per revolution. With its low inertia, high slew speed, and small size, the R60 is an excellent choice for use in medical electronics, capstan drives on computer peripherals, printer drive motors and robotic positioning drives, where accuracy and space utilization are prime considerations.

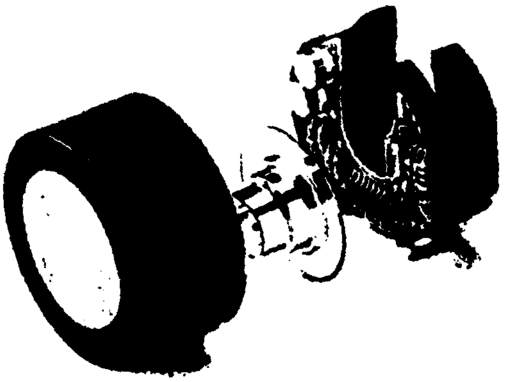
FEATURES

R60 Series

- ▲ *Ease of assembly and adjustment on motor.*
- ▲ *Chrome on glass disk.*
- ▲ *2 hole mounting pattern.*
- ▲ *Radial-Line Sensor Array.*
- ▲ *Hubs for up to 8mm shaft.*
- ▲ *Many standard pulse rates.*
- ▲ *Five types of standard electrical outputs.*
- ▲ *Consult factory for special options.*

ROBBINS MYERS

Robbins & Myers / Renco
26 Coromar Dr.
Goleta, CA 93117-3094
(805) 968-1525
(800) 589-8007
FAX (805) 968-7065
TWX (910) 334-1180



Specifications

MECHANICAL DATA	R60
Mechanical Outline	See Figure 1 & 2
Moment of Inertia	1.6 (10^{-4}) oz-in-sec^2
Angular Acceleration	100,000 rad/sec^2
Slew Speed	9,000 RPM
Hub Sizes	See Table I
Air Gap Setting	See Table II
Cable Wiring	See Table IV

ELECTRICAL DATA	R60
Input Power Requirements	
Type 1 Sine Wave Models	5 VDC ± 5% @ 75 ma
Type 2 Amp. Sine Wave Models	+ 5 VDC ± 5% @ 100 ma −15 VDC ± 10% @ 30 ma
Type 3 Square Wave Models TTL	5 VDC ± 5% @ 125 ma max.
Type 4 CMOS Compatible	5V ± 10% @ 100 ma max.
Type 5 TTL complementary	5 VDC ± 5% @ 125 ma
(Open collector available, consult factory.)	
Phasing	A leads B by 90° ± 36° electrically for CCW rotation viewed from cover end.
Code	Incremental
Illumination Source	LED
Sensors	Phototransistor radial array
Operating Frequency	
Data	To 100 KHz
Flutter	1% max.

ENVIRONMENTAL DATA	R60
Operating Temperature	0° to + 70°C
Storage Temperature	−30° to + 90°C
Humidity	90% relative, no condensation

FIGURE 1

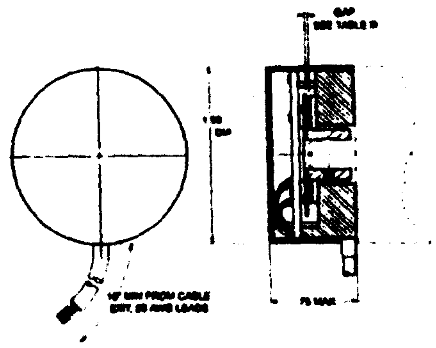


FIGURE 2

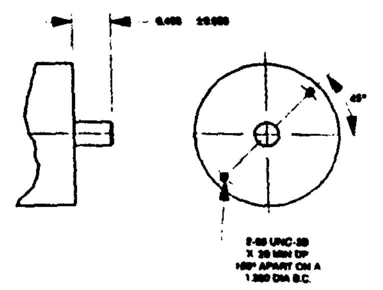


TABLE 1

HUB SIZE	
SHAFT SIZE +.0000 −.0002	SPECIFY
.1873	3/16
.2497	1/4
.3122	5/16
.1966	5MM
.2148	6MM

TABLE 2

GAP SETTING		
RESOLUTION	GAP +.000 −.002	
	TYPE 1, 3, 4 & 5	TYPE 2
UP TO 750	.005	.012
751 TO 1024	.004	.008
1025 TO 1875	±.001	±.001

TABLE 3

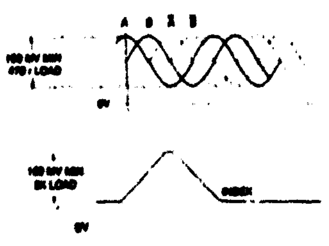
OPERATING VOLTAGE OPTION	
VOLTAGE	DESIGNATION
5.0	5
+5 & −5	±5

TABLE 4

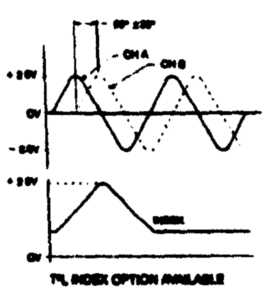
OUTPUTS				LEAD COLOR
TYPE 1	TYPE 2	TYPE 3 & 4	TYPE 5	
A	A	A	A	WHT
$\bar{A}$	—	—	$\bar{A}$	YEL
B	B	B	B	GRN
$\bar{B}$	—		$\bar{B}$	BLU
INDEX	INDEX	INDEX	INDEX	ORG
+5V	+5V	+5V	+5	RED
—	−5V	—	—	BLU
—	—	—	$\overline{INDEX}$	BRN
GND	GND	GND	GND	BLK

OUTPUT CONFIGURATION

TYPE 1 OUTPUT: *Differential Sine Wave*

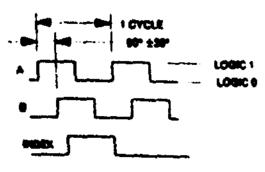


TYPE 2 OUTPUT: *Amplified Sine Wave*



TTL INDEX OPTION AVAILABLE

TYPE 3 OUTPUT: *TTL Compatible*
TYPE 4 OUTPUT: *CMOS*



NOTE: COMPLEMENTARY OUTPUTS ARE NOT SHOWN, BUT ARE AVAILABLE

ORDERING INFORMATION *To order, supply the appropriate designation, see codes shown below*

R80 — — — — — — S

Hitachi 8-bit Microcomputer

HD63140

UPP (Universal Pulse Processor)

APPLICATION NOTE

—SOFTWARE—

HITACHI

ADE-502-002

SECTION 1. GENERAL DESCRIPTION

The UPP can process up to 24 pulse signals (8 of which do not have I/O pins) simultaneously, measure the cycle time of an input pulse signal, and count the edge number of input pulse signals. It can also output pulse signals whose cycle time and duty cycle are programmable.

1.1 Features

The UPP provides the following functions:

- o 15 commands for pulse I/O functions
- o 24 x 16-bit programmable registers
- o 24 programmable I/O ports (8 of which do not have I/O pins)
- o Pulse width resolution of 0.5 µs to 5 µs at maximum speed operation (depending on the number of specified functions)
- o Programmable detection of falling edge, rising edge, or falling and rising edges of input signal
- o Interrupt request output through I/O ports

In order to provide I/O processor flexibility, the UPP includes I/O microprogrammable RAM where I/O functions can be written in the form of a function table. This table specifies counter/timer functions, by a format description which corresponds to the specification of a counter/timer function. The resolution of a counter/timer function can be enhanced by describing the corresponding format repeatedly in the function table.

The UPP can 'combine' counter/timer functions in the function table by using flexible registers and I/O pin assignment. This 'combination' means that registers in the register file functioning as counter, compare, or capture registers along with I/O pins can be shared by multiple counter/timer functions.

Fig. 1-1. shows the UPC block diagram.

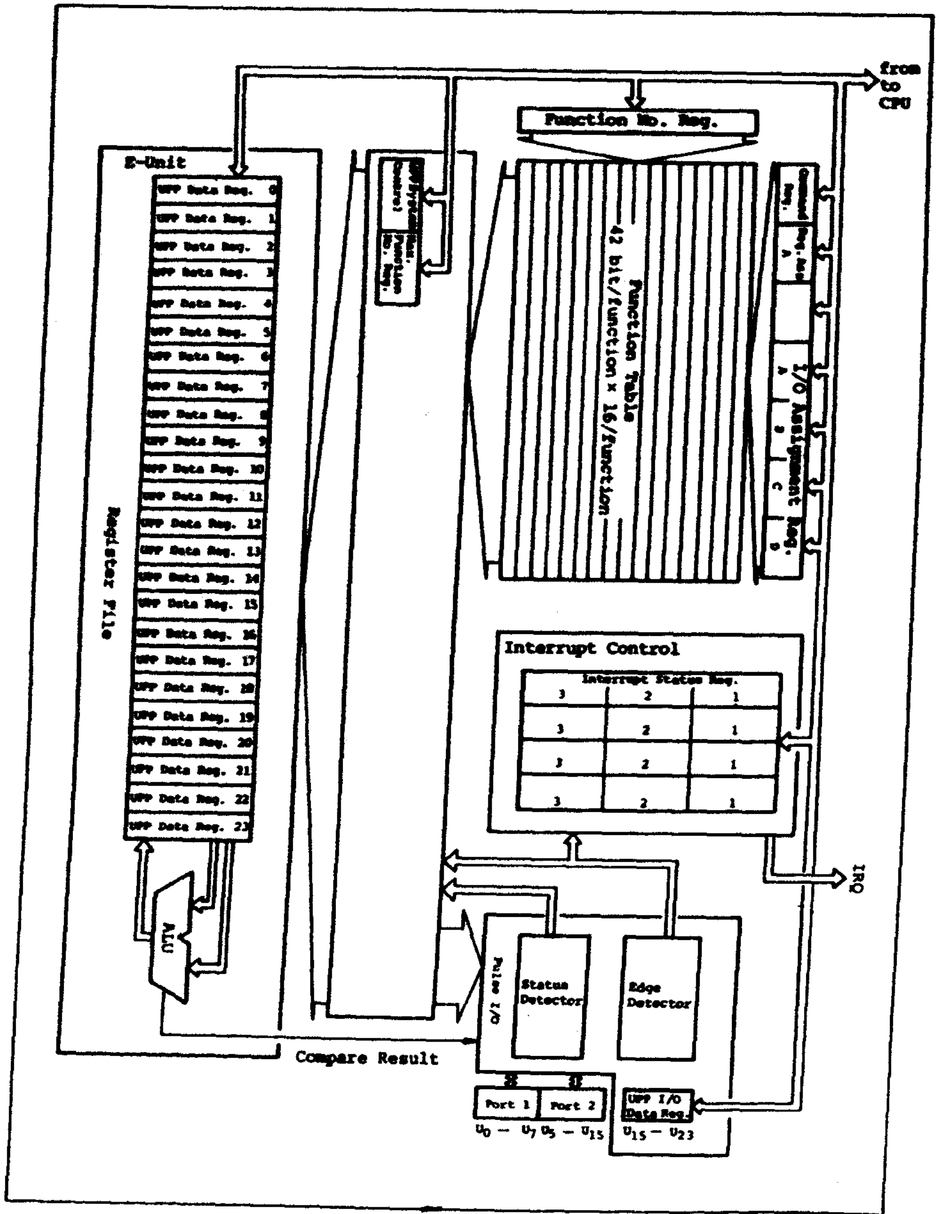


Fig. 1-1. UPC Block Diagram

1.2 Register Names and Descriptions

Table 1-1 lists the names and descriptions of UPP registers.

Table 1-1. UPP Register Names and Descriptions

Abbreviation	Name	Description
USCR	UPP System Control Register	Controls activation and halt of the UPP
MFNR	Maximum Function Number Register	Specifies the number of functions executed by the UPP and the resolution
FNR	Function Number Register	Specifies the function number
CMR	Command Register	Specifies the command code
RASRA	Register Assignment Register A	Specifies the number of the data register functioning as a counter, timer or shifter
RASRB	Register Assignment Register B	Specifies the number of the data register functioning as a compare or capture register or buffer
IOARA	I/O Assignment Register A	Specifies the pin number for external clock signal input, or shift clock signal input
IOARB	I/O Assignment Register B	Specifies the pin number for sampling signal input, trigger signal input, set signal input, or reset signal input
IOARC	I/O Assignment Register C	Specifies the pin number for pulse signal output
IOARD	I/O Assignment Register D	Specifies the input pin number for direction signal, gate signal, or two-phase pulse signal
IER3	Interrupt Enable Register 3	Enables or disables interrupt requests for ports U23 to U16
IER2	Interrupt Enable Register 2	Enables or disables interrupt requests for ports U15 to U8
IER1	Interrupt Enable Register 1	Enables or disables interrupt requests for ports U7 to U0
ISCR3	Interrupt Status Clear Register 3	Clears the interrupt request flags for ports U23 to U16
ISCR2	Interrupt Status Clear Register 2	Clears the interrupt request flags for ports U15 to U8
ISCR1	Interrupt Status Clear Register 1	Clears the interrupt request flags for ports U7 to U0
UIOR	UPP I/O Register	I/O data register for U23 to U16
UDR0 to UDR23	UPP Data Registers 0 to 23	Can function as counter, timer, shifter capture register, or compare register
UOR2	UPP Output Register 2	Output register for U15 to U8
UOR1	UPP Output Register 1	Output register for U7 to U0
UCER2	UPP Contact Enable Register 2	Configures port 2 as CPU port or UPP port
UCER1	UPP Contact Enable Register 1	Configures port 1 as CPU port or UPP port

1.3 Command Names and Descriptions

Table 1-2 lists names and descriptions of the UPP commands.

Table 1-2. Command Names and Descriptions

Abbreviation	Name	Description
FRS	Free Running Counter/Timer With Sampling	Counting of pulse signal
INS	Interval Counter/Timer With Sampling	Measurement of pulse signal cycle
UDS	Up-Down Counter/Timer With Sampling	Counting of direction definition signal
GTS	Gated Counter/Timer With Sampling	Measurement of gate signal width
FRC	Free Running Counter/Timer With Compare	Output of pulse signal
INC	Interval Counter/Timer With Compare	Output of pulse cycle
PWC	Pulse Width Counter/Timer Witn Compare	Output of pulse width
OSC	One Short Counter/Timer With Compare	Output of one short pulse
FFC	Fifty-Fifty Duty Counter/ Timer With Compare	Output of pulse with a 50% duty cycle
TPC	Two-Phase Up-Down Counter	Counting of two-phase pulse signal
GTC	Gated Counter/Timer With Compare	Definition of gate signal width
CTO	Combination Trigger One Shot Counter/Timer	Output of one-shot pulse with trigger enable
SIT	Shift Input	Input of shift
SOT	Shift Output	Output of shift
SPO	Shift Parallel Output	Output of 8-bit parallel data

Appendix E

Program Listings

Listing Details - #1	
Program Name:	*caplin.csl*
Application:	*ACSL*
Description:	*Capstan drive model for linearisation into state-space matrices*

```
PROGRAM CAPSTAN DRIVE
"SIMULATION OF CAPSTAN FILM DRIVE WITH BRUSHLESS MOTORS S-1002"
"USING CURRENT FEEDBACK FROM BRU100 SERVO DRIVE UNITS"
"=========================================" "
Model used to obtain linearised state space model"

INITIAL
        "RCAP  - Capstan Radius      ,          KT - Motor Voltage Constant"
        "TF    - Motor Friction Torque , DAMP - Motor Viscous Damping"
        "KB    - Back EMF constant  ,   L - Motor Inductance"
        "R     - Motor Resistance   ,   J - Motor Rotor Inertia"
        "JCAP  - Capstan Inertia  ,    DCAP - Capstan Damping Constant"
        "Fric -  Capstan Friction"
        CONSTANT RCAP=0.0125 , KT=0.075 , TF=0.00565
        CONSTANT DAMP=1.34646E-05 , KB=0.07544
        CONSTANT L=0.0017 , R=2.5 , J=2.61E-06 , JCAP=2.0E-05
        CONSTANT IA1IC=0.0 , IA2IC=0.0 , TAF=0.0
        CONSTANT PI=3.1415926
        CONSTANT C=33.0 , K=66666.66  $"FREE FILM LENGTH = 0.3M"
        CONSTANT Fric = 0.0001 CONSTANT IA1Z=0.0,IA2Z=0.0
        "Start-up Initial Conditions"
        THD1ic=0.0 THD2ic=0.0 IA1ic =0.0 IA2ic =0.0
END $"of initial"

DYNAMIC

        CINTERVAL CINT = 0.0001
        NSTEPS=1
        MAXTERVAL MAXT=0.00001
        CONSTANT  TSTP = 0.0

DERIVATIVE

"CAPSTAN DRIVE EQUATIONS OF MOTION"
        THDD1=(KT*IA1-RCAP*TXEN-DAMP*THD1-Fric*THD1)/(J+JCAP)
        THDD2=(KT*IA2-RCAP*TXEN-DAMP*THD2-Fric*THD2)/(J+JCAP)
        THD1=INTEG(THDD1,THD1ic)
        THD2=INTEG(THDD2,THD2ic)
        X1D=THD1*RCAP
        X2D=THD2*RCAP

"OUTPUTS TO BE CONTROLLED"
        "FILM TENSION DISTURBANCES"
                TXDOT= K*RCAP*(THD2+THD1)+C*RCAP*(THDD2+THDD1)
                TXEN =INTEG(TXDOT,0.0)
        "SPEED OVER APERTURE"
                Speed = (X2D - X1D)/2.0
"*************** CONTROLLER SECTION ***************
```

```
"CONTROLLER SECTION CONSISTS OF BRU-100 AMP DRIVING"
"A S100-2 BRUSHLESS DC MOTOR"

"MOTOR 1 "
CONSTANT Ez1=0.0,Ref1 = 0.0
CONSTANT GAINam = 3.0 $"Gain of BRU100 current amplifier"
CONSTANT Tia1 = 0.0005
        ia1 = integ((V1in-(ia1))/(Tia1),0.0)
        V1in = Ref1 + Ez1
"MOTOR 2 "
CONSTANT Ez2=0.0,Ref2=0.0
CONSTANT Tia2 = 0.0005
        ia2 = integ((V2in-(ia2))/(Tia2),0.0)
        V2in = Ref2 + Ez2

END $" of Derivative"

END $" of Dynamic"

TERMINAL

        TERMT(T.GE.TSTP)

END $" of Terminal"

END $" of Program"
```

Listing Details - #2	
Program Name:	*capest.csl*
Application:	*ACSL*
Description:	*Capstan drive model with full-state feedback + integrator + estimator digital controller.*

```
PROGRAM CAPSTAN WITH ESTIMATOR
"SIMULATION OF CAPSTAN FILM DRIVE WITH BRUSHLESS MOTOR S-1002"
"==================================================="

INITIAL
" Define Matrix Manipulation Macros "

"-------------------Matrix Multiply. Calling sequence is: "
"                                        "
"        MMUL(C = A, B)                  "
"                                        "
"  This defines a new matrix C of dimension col(A) by row(B) and "
"  performs the matrix multiplication "

"-------------------matrix add. Up to 4 matrices can be "
"  added into an output matrix which is created automatically. "
"  Calling sequence:                          "
"                                             "
"  MADD(Y = A, B, ..., D, E)                  "
"                                             "
"  where the input matrices must have exactly the same dimen- "
"  sions (both rows and columns) and this will be the size of "
"  the output matrix Y.                       "

"-------------------Matrix Negate. The output matrix is  "
"  created and the input matrix is moved into it, changing the  "
"  sign of each element on the way "
MACRO MACRO MNEGAT(p, q, r)

" Define Constants"
REAL IntErr(1,1)
CONSTANT RCAP=0.0125 , KT=0.075 , TF=0.00565
CONSTANT DAMP=1.34646E-05 , KB=0.07544
CONSTANT L=0.0017 , R=2.5 , J=2.61E-06 , JCAP=2.0E-05
CONSTANT IA1IC=0.0 , IA2IC=0.0 , TAF=0.0
CONSTANT TSTP=0.0, PI=3.1415926
CONSTANT TFRUN=0.00565
CONSTANT C=33.0 , K=66666.66  $"FREE FILM LENGTH = 0.3M"
CONSTANT IA1Z=0.0,IA2Z=0.0
CONSTANT DLTC=0.0
CONSTANT Fric=0.0001 $"Capstan Friction"



"Start-up Initial Conditions"
CONSTANT X1DIC=0.0,X2DIC=0.0,TENIC=0.0
CONSTANT THD1IC=0.0 THD2IC=0.0
```

```
CONSTANT U1(1,1)=0.0,U1(2,1)=0.0
CONSTANT U2(1,1)=0.0,U2(2,1)=0.0
CONSTANT U(1,1)=0.0,U(2,1)=0.0
CONSTANT UL(1,1)=0.0,UL(2,1)=0.0
CONSTANT UT1=0.0,UT2=0.0
CONSTANT IntErr(1,1)=0.0

"Noise Parameters"
CONSTANT noise1=0.0,noise2=0.0
CONSTANT noise3=0.0,noise4=0.0

"Switches"
CONSTANT sw1=0.0,sw2=0.0

"Initialise filter states"

DO L998 Irow = 1,5
 DO L998 jcol = 1,5
  Xhat1(Irow,jcol) = 0.0
L998..CONTINUE

        sigNse = 1.0 / SQRT(MAXT)
        CINTERVAL CINT = 0.0001
        NSTEPS=1
        MAXTERVAL MAXT=0.00001

END $"of Initial"

DYNAMIC
DERIVATIVE

"CAPSTAN DRIVE EQUATIONS OF MOTION"

        THDD1=(KT*IA1+RCAP*(TDis1)-DAMP*THD1-Fric*THD1)/(J+JCAP)
        THDD2=(KT*IA2+RCAP*(TDis2)-DAMP*THD2-Fric*THD2)/(J+JCAP)

        THD1=INTEG(THDD1,THD1IC) + sw1*N1sin
        THD2=INTEG(THDD2,THD2IC)   sw2*N2sin

X1D=THD1*RCAP
X2D=THD2*RCAP

"OUTPUTS TO BE CONTROLLED"
        "FILM TENSION DISTURBANCES"

        N1=noise1*GAUSS(0.0,sigNse) $"Noise - film between capstans"
        N2=noise2*GAUSS(0.0,sigNse) $"Noise - External"
```

```
            TXDOT=K*RCAP*(THD2+THD1)+C*RCAP*(THDD2+THDD1)

    "Limit Tension is. Tension can never be negative"
    CONSTANT Tmin=0.0,Tmax=100.0,ExtDis=0.0
    TXEN=INTEG(TXDOT,TENIC)
        Ten = BOUND(Tmin,Tmax,TXEN)

        TDis1 = (ExtDis-Ten) + N1
        TDis2 = (ExtDis-Ten) + N2

        "SPEED OVER APERTURE"
                SPEED=(X2D - X1D)/2

************* CONTROLLER SECTION *************
"CONTROLLER SECTION CONSISTS OF BRU-100 AMP DRIVING"
"A S100-2 BRUSHLESS DC MOTOR"

"Process Noise"

NI1 = noise3*GAUSS(0.0,sigNse)
NI2 = noise4*GAUSS(0.0,sigNse)

"MOTOR 1 "
CONSTANT GAINam = 3.0  $"Gain of current feedback amplifier"
CONSTANT Tia1 = 0.0005


        Ia1 = Integ((V1in-(Ia1))/(Tia1),0.0)
        V1in = UT1 + NI1

"MOTOR 2 "
CONSTANT Tia2 = 0.0005
        Ia2 = Integ((V2in-(Ia2))/(Tia2),0.0)
        V2in = UT2 + NI1

END $" of Derivative"

TERMT(T.GE.TSTP)

DISCRETE ADC
        INTERVAL TSAMP=0.00015
PROCEDURAL
"STATE FEEDBACK"
CONSTANT TenG=1.0
CONSTANT Ref(1,1) = 1.0
CONSTANT Ref(2,1) = 1.0
"Reference States"
        REAL Nx(5,2),Ref(2,1)
```

```
          MMUL(XR=Nx,Ref)
"Estimator - KALMAN FILTER"
          "Time Update"
                    REAL PHI(5,5),GAMMA(5,2),UL(2,1),Xhat1(5,5)
                    MMUL(F=PHI,Xhat1)
                    MMUL(G=GAMMA,UL)
                    MADD(Xbar1=F,G)
          "Measurement Update"
                    "Prediction error"
                    REAL Y(2,1),Lkalm(5,2),H(2,5)
                    Y(1,1) = Ten
                    Y(2,1) = Speed
                    MMUL(Ybar=H,Xbar1)
                    MNEGAT(NYbar=Ybar)
                    MADD(ERRy=Y,NYbar)
                    MMUL(Ky=Lkalm,ERRy)
                    MADD(Xhat=Xbar1,Ky)
"Xhat1 = Xhat"
          DO L999 Irow = 1,5
          DO L999 jcol = 1,5
                    Xhat1(Irow,jcol) = Xhat(Irow,jcol)
          L999..CONTINUE
"Error for feedback"
          REAL Err(5,1)
          Err(1,1) = Xr(1,1) - ia1
          Err(2,1) = Xr(2,1) - ia2
          Err(3,1) = Xr(3,1) - thd1
          Err(4,1) = Xr(4,1) - thd2
          Err(5,1) = Xr(5,1) - (ia1 + ia2)
" Error * K"
          REAL KDLQR(2,5)
          MMUL(U1=KDLQR,Err)
" Integral tension error"
          TenErr = Ref(1,1) - Ten
          IntErr(1,1) = IntErr(1,1) + TenErr * TSAMP
" Integral Error * Integral Gain"
          REAL KI(2,1)
          MMUL(U2=KI,IntErr)
" Combined control effort"
          MADD(U=U1,U2)
" Make present control effort last"
          UL(1,1) = U(1,1)
          UL(2,1) = U(2,1)
END $"OF PROCEDURAL"

SCHEDULE DAC .AT. T + DLTC
END $"OF ADC SECTION"
```

```
DISCRETE DAC
"Output control effort"
UT1 = BOUND(-10.0,10.0,U1(1,1)+U2(1,1))
UT2 = BOUND(-10.0,10.0,U1(2,1)+U2(2,1))

END $"OF DAC SECTION"

END $" of Dynamic"

END $" of Program "
```

Listing Details - #3	
Program Name:	*caplin.ctr*
Application:	*CTRLC (ACSL Interface)*
Description:	*Linearisation of ACSL model caplin.csl. State-space matricies formed and saved.*

```
// Linearisation of CAPLIN.CSL ACSL Model
Disp('Linearisation of ACSL Model')

analclear           // clear the ANALYZ state of ACSL
c2alist('clear')    // clear the list of variables

contr('ez1,ez2')    // define ACSL inputs
observ('txen,speed')// define ACSL outputs

[t]=start;          // run ACSL simulation with zero time to initialize

Disp('Linear Model Description')

[a,b,c,d]=Jacobian  // Linear Model Description

Disp('Save state-space matrices to file')
save capstan.mat
```

Listing Details - #4	
Program Name:	*capest.ctr*
Application:	*CTRLC*
Description:	*Full-state feedback + integrator + estimator based on linearised model of capstan drive.*

```
// MIMO Capstan drive control design
// Reference controller - Full-state feedback with integrator and estimator


// Define external procedures
deff refi // Reference input
deff zohplot // Zero-order hold plot
deff dstep // Step input
deff magdb // Conversion to db


load capstan.mat // Load linearised state-space matricies
// Add integral state term - augmented model
C=[0  0  0  0    0    1
  0  0  0 -.0063 .0063 0
  1  0  0  0    0    0]
// Actual output for estimator
CE=[ 1 1  0   0  0
   0 0  1   1  0 ]
// Add tension integral state
CI=[0 0 0 0 1];
D=zrow(2,5);
// Sample time
Ts = .00015;
// Continuous to discrete
[phi,gam]=c2d(A,B,Ts);
// Augmented model
phia=[1 CI;zrow(5,1) phi];
gama=[0 0;gam];
// LQR weightings
Q2=[1 0
      0 1];
Q1BAR=[1  0   0
          0 100  0
          0 0    1];
Q1=C'*Q1BAR*C;
// Feedback gains LQR
KA=dlqr(phia,gama,Q1,Q2);
KA=real(KA);
// Measurment and process noise matricies
Rv=[0.01 0;0 0.0001];
Rw=[0.0001 0;0 0.0001];
// Estimator Gains
L=dlqe(phi,gam,CE,Rw,Rv);
L=real(L);
// Closed-loop with estimator
LC=L*CE;
phie=phi-LC;
// Full-state feedback gains
```

```
K=KA(:,2:6);
// Integral feedback gains
KI=KA(:,1);
// Reference input matrix
[NX,NU,NBAR]=REFI(phi,gam,CE,K);
// Closed-loop full system
BK=gam*K;
phic=[1 CI zrow(1,5);-gam*KI phi -BK;-gam*KI LC phi-BK-LC];
Ccl=[zrow(2,1) CE zrow(2,5)];
Bcl=[-1 0 0 0 0;BK*NX zrow(5,2) gam(:,1);BK*NX L zrow(5,1)];
// Control terms
Du=[K*Nx zrow(2,3)];
Cu=[-KI zrow(2,5) -K];
// Unit step input
// Time series
n=50;
t=0:Ts:(n-1)*Ts;

disp('reference 1')
disp('   step')
erase
[y1,x1,ref1]=dstep(phic,Bcl,Ccl,D,1,n);
u1 = dstep(phic,Bcl,Cu,Du,1,n);
[xb1,yb1]=zohplot(t,u1);
plotting..
disp('Reference 2')
disp('   step')
[y2,x2,ref]=dstep(phic,Bcl,Ccl,D,2,n);
u2=dstep(phic,Bcl,Cu,Du,2,n);
[xb2,yb2]=zohplot(t,u2);

// Computation of Transfer Function Matrix
// of Closed loop System.

// Convert back to continous form
[acl,bcl] = d2c(phic,Bcl,ts);
disp('Closed Loop Bode Plot')
w = logspace(2,5); // Set up frequency vector
// Bode plots
[mag1,phas1]=bode(acl,bcl,ccl,d,1,w);
[mag2,phas2]=bode(acl,bcl,ccl,d,2,w);
[mag1] = dbmag(ccl,mag1);
[mag2] = dbmag(ccl,mag2);
plotting....
```

Listing Details - #5	
Program Name:	*capestac.ctr*
Application:	*CTRLC - ACSL (Interface)*
Description:	*Full-state feedback + integrator + estimator controller tested on ACSL model description of capstan drive.*

```
// []=capestacsl(phi,gamma,H,kdlqr,ki,lkalm,nx,tstp)
// ACSL interface procedure
// Test linear model controller on non-linear plant with
// Kalman Filter including added noise/disturbances.

c2alist('phi,gamma,H,kdlqr,ki,lkalm,nx,tstp') // pass to ACSL model

[t,ten,speed,ia1,ia2,ut1,ut2] = start; // run ACSL model (no noise)
plotting....

// tension distrubances
noise1 = 0.001; // Between capstan drive
noise2 = 0.001; // External disturbances
ExtDis = 1.0;  //  External tension (constant)

c2alist('noise1,noise2,ExtDis') // pass to ACSL model
[t,ten,speed,ia1,ia2,ut1,ut2] = start; // run ACSL model (Tension Disturbance)
plotting.....
// Process noise (control input)
noise1 = 0.0; // Between capstan drive
noise2 = 0.0; // External disturbances
ExtDis = 0.0;  //  External tension (constant)
noise3 = 0.01; // motor drive 1
noise4 = 0.01; // motor drive 2

c2alist('noise1,noise2,noise3,noise4,ExtDis') // pass to ACSL model
[t,ten,speed,ia1,ia2,ut1,ut2] = start; // run ACSL model (process noise)
plotting....
```