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	Roll-to-roll tension controller design based on fuzzy logic for manufacturing printed **Ganeshthangaraj Ponniah 2012**	

ATHESIS

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Roll-to-roll tension controller design based on fuzzy logic for manufacturing printed electronics

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Roll-to-roll tension controller design based on fuzzy logic for manufacturing printed electronics

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To

Tolerant parents

Good teachers

Persistent friends

Nourishing motherland

And god

Acknowledgement

I am most grateful to my parents who have from the very beginning indulged my thirst for knowledge besides providing a comfortable atmosphere for learning. Their impeccable sense of morality has always been my guiding light. I am also lucky to have been educated by many talented teachers all the way from my childhood to this day.

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Contents:

List of figures:

Abstract

Roll-to-roll (R2R) system has been employed successfully in a variety of industries such as graphical printing, textiles, films, foils and many more converting industries. Printed electronics is a newly emerging technology that is said to revolutionize electronics industry by providing new cheaper alternatives to the conventional electronics. It is believed to be the future of disposable electronics, organic photovoltaic, organic light emitting diodes, RFID, E-paper, and many more yet unexplored potential of flexible electronics. Several of the above mentioned have been achieved on a laboratory scale, but very few have been commercialized successfully. This thesis attempts to explore the potential of R2R system to mass produce printed electronic components. The focus being on application of fuzzy logic to control the tension of the web on which printing takes place. Even with fuzzy logic several different approaches have been tried depending on the printing process. Especially worth noting is the absence of system model while designing the controllers. Rather the existing controllers are replaced with better fuzzy controllers, or are used to augment the existing controllers. Occasionally simple statistical tools have been employed to help develop the intuition that is the core of fuzzy logic. Based on the intuition and a thorough study of the printing process itself, control architectures have been developed for two printing processes, namely offset printing and slot die coating. Further a new model less approach has been used to prevent propagation of tension from one tension span to the next, which is a very commonly observed phenomenon in R2R systems. This will not just help printed electronics but will also be beneficial in disturbance prone converting industries.

1. Roll-to-roll system

1.1. Introduction to Roll-to-roll system

R2R system has come a long way since its initial application. R2R system is typically made up of a number of rollers that are held by bearings. The bearings in turn are fixed on the machine frame. The machine frame is ideally made of vibration dampening steel although more flimsy machine frames can be seen in literature. Material processed by the R2R system is known as web. Web may be defined as a material whose width is orders of magnitude larger than its thickness and length being orders of magnitude larger than the width- this definition holds good for paper, textile, films and foils. Although an R2R system may process materials that have width and thickness in the same order of magnitude, such as threads and ropes, in this thesis we deal with only web. The function of R2R system is to unwind material in the form of web, process it, and either cut it (as in newspaper printing), or rewind it. The processing may involve a number of things, like printing (slot die, offset, gravure, electro-hydro-dynamic printing, etc), plasma treatment, static removal, curing etc. Factors that have the most effect on the processing of web are

- Web tension, and
- Lateral and longitudinal registration.

As mentioned above, the web is transported via the R2R system by a number of rolls. These rolls fall into two categories, driven rolls and idle rolls. Besides these at unwind and rewind sections pneumatic expanding mandrels are used to hold and turn reels of the web. The driven rolls are turned by servo motors. Web tension may be denoted in two ways, as longitudinal force exerted by the web as a result of the strain in the web and as longitudinal force per unit width of the web. Both definitions are commonly used in industry as well as academia. Basically the R2R system is designed to move the web from unwind to the rewind section through the processing span, while applying a suitable tension without permanently deforming the web-unless that is part of the process. There are some rules of thumb that are commonly applied while using the R2R system for conventional applications; these have also been cited in scholarly work. But printed electronics is very distinct from the graphical printing industry. The requirements of precision of tension and registration are far greater and the processes themselves are very different from conventional printing industry. An R2R system can assume many forms depending on the purpose for which it is built. The complete R2R system used in this work is shown in figure 1.1, illustrating each individual component or section of the system.

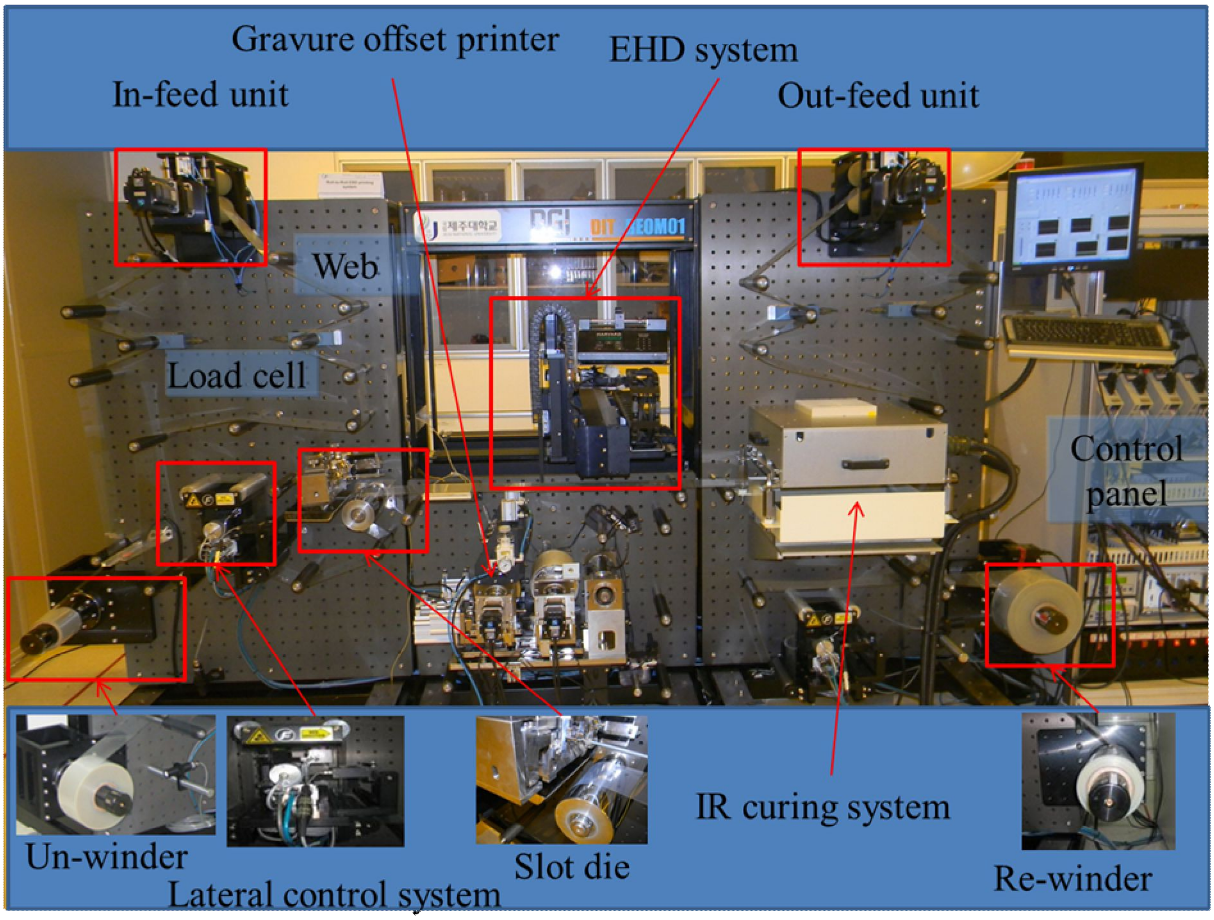


Figure 1.1 R2R system

1.2. Importance of R2R system in printed electronics

Electronics industry has over several decades, perfected techniques to fabricate electronics circuits. These circuits are typically made up of a number of layers of semiconductor materials with specific electronic properties. Fabrication of these layers is a lengthy process known as lithography. Several variants of lithography exists depending upon the precision required. Typical lithography process involves first a coating process such a sputtering upon a silicon wafer, followed by application of photoresist, followed by exposure of the photo-resist to curing beam through a mask, then the unexposed photo-resist is washed away with the aid of an appropriate solution. This is followed by etching to remove unwanted region of the coating.

Finally an appropriate solvent is used to remove the remainder of the photoresist. The above steps are illustrated in figure 1.2 (a).This whole process can produce only one layer. And the above description is very conservative as more intermediate steps may be involved depending on the process and material. Since a devices is usually (except may be resistor) nevermade of a single layer the total steps will be very large. The reason this lengthy process is employed is because it is effective in manufacturing reliable and precise electronic circuits ranging from microns to hundreds of nanometer size scale. Comparison of 1.2 (a) and (b) gives a good idea of the difference in the fabrication time and effort between conventional and printed electronics.

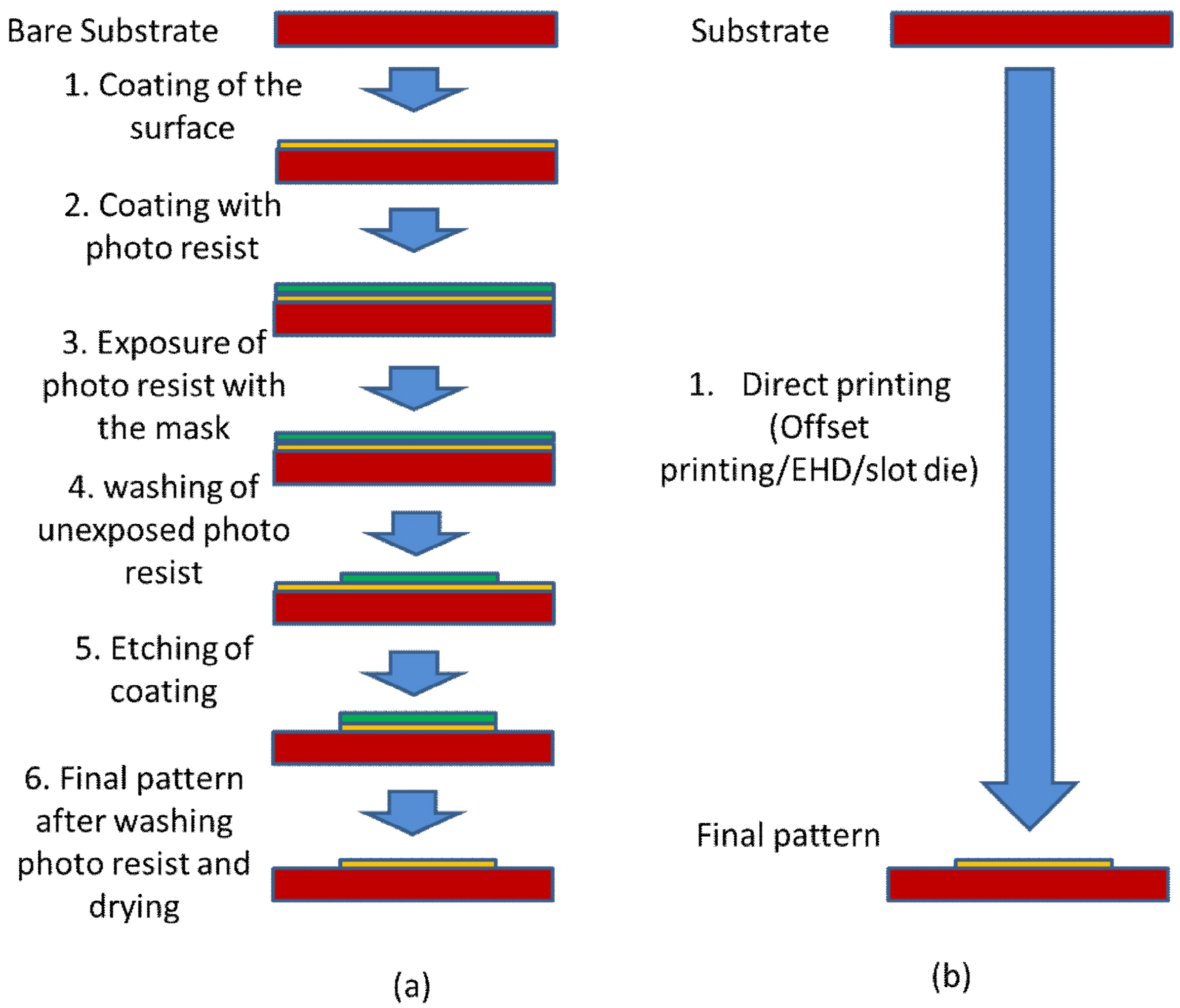


Figure 1.2 (a) Conventional electronics manufacture; (b) Printed electronics manufacture

While it has already been established that conventional silicon based electronics cannot be replaced in the near future by printed electronics, printed electronics will play a crucial role in the fabrication of electronics where the accuracy and size of the circuits are not very important. Especially useful will be the fabrication of printed circuits that have resolution of a few microns and above, and large area printed electronics. These could be manufactured more economically by direct printing method than by conventional means.

R2R based fabrication is the next logical evolutionary path of printed electronics primarily due to its ability to mass produce. Flexible solar cellsand Organic light emitting diodes (OLED) have already been manufactured on the R2R system. Although not yet commercialized, they hold great promise. The flexible solar cell/organic photovoltaic (OPV) and OLED demand will be great in the coming decade. OPV's have been proven to be less efficient than the conventional solar cells, but it is believed that their cost of production will be considerably reduced by the fact that they can be mass produced on R2R system. OLED is also similarly expected to be in demand and is expected to completely dominate the lighting industry. RFID antenna has been printed in R2R system. The accompanying circuit is too complex to be printed commercially; hence a combination of printed and conventional electronics is currently used in RFID tags. While some of the limitations in the R2R based commercialization of some of these products is due to absence of suitable material in the device, some can be attributed to the R2R process itself. Electronics is expected to be printed on flexible substrate, but electronic devices that thin are flimsy and may not successfully survive the R2R processing. R2R industry has its own guidelines which are not very sympathetic towards printed electronics. In this context it will be wise to develop controllers and tension and velocity control guidelines specifically for manufacturing printed electronics in R2R system. It is also crucial to develop controllers custom tailored for R2R systembased printing and coating techniques.

2. Web tension control system

2.1. Hardware

2.1.1. Servo pack

Servo packs are the most crucial part of any R2R system. Each servo pack has two components

- A servo motor.
- A servo amplifier.

The purpose of a servo pack is to provide a torque or velocity output at the output shaft of the motor following as precisely as possible the input command given to it, which may be in the form of analog or digital signal. Originally servo packs were designed to follow position control commands. But the automation industry has developed requirements for different specifications of servo packs. The servo packs currently come in a number of configurations, but usually they all aim to control the position, velocity and torque at the output shaft of the servo motor. Nowadays the versatile servo packs are designed to simultaneous control two or more combinations of torque, velocity and speed. One of the most commonly used servo motors in CNC machine spindles, works on positions control mode and is operated by introducing pulse trains. The servo pack reads the pulse train and moves the motor through a specific angle corresponding to each pulse sensed. Another common configuration for the servo mode is the torque velocity combination. This is often used in converting industry. There are two variants of this combination:

- Velocity control with torque limit.
- Torque control with velocity limit.

In the first instance the velocity is tightly controlled subject to torque limit. Thus the velocity is followed based on the command velocity by changing the torque to the motor, but if the torque ever exceeds the torque limit command the velocity tracking error is ignored. In the second instance the torque is controlled tightly subject to velocity limit. Both these modes are used in different regions of the R2R system. Every R2R system can be divided into sections called spans. Basically it is the length of web between two consecutive driven rolls occurring on the web as it travels from the roll from which it is unwound(un-wind section) to the roll on which it is rewound(re-wind section). The tension in each span has to be set according to the process being performed in the span such as un-wind, printing, re-wind etc. In any R2R system there will always be a driven roller that controls master velocity of the system. Usually it's a nip roller. A nip roller may be defined as a driven roll that is hold the web against another roller that applies a pressure so that there is no slip between the web and the nip roller. The master velocity roller is driven by a servo motor that is usually operated in velocity mode with torque limit. Tension in the spans that follow the master velocity roller are controlled by driven rollers on the downstream end of the span, while those spans before the master velocity roller are controlled by driven rollers on the upstream end of the span. The tension controlling rollers are often set on torque control mode with velocity limit. The terminology related to spans is illustrated in figure 2.1.

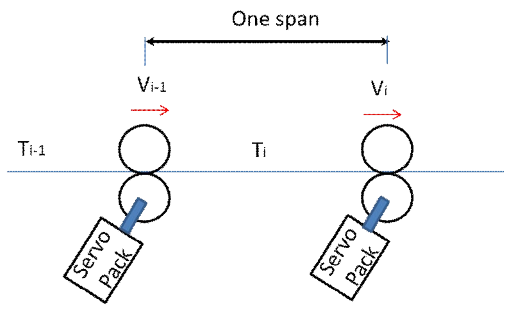


Figure 2.1(a). One web span between two driven rolls. T is the tension of the web and subscript gives the span number. V is the linear velocity of web at the specified roller.

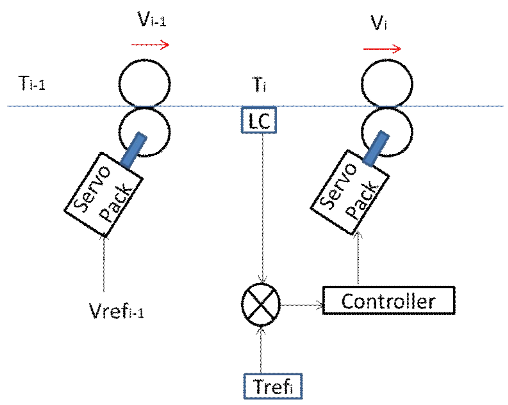


Figure 2.1 (b). Control of tension in a span after the master velocity roller. LC is the load cell. Tref is the reference tension of the given span and Vref is the reference velocity of master velocity roll.

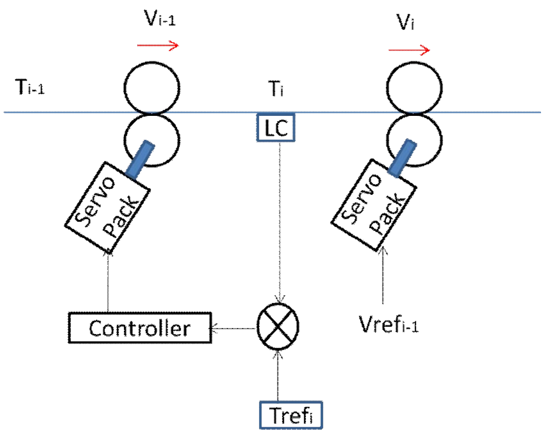
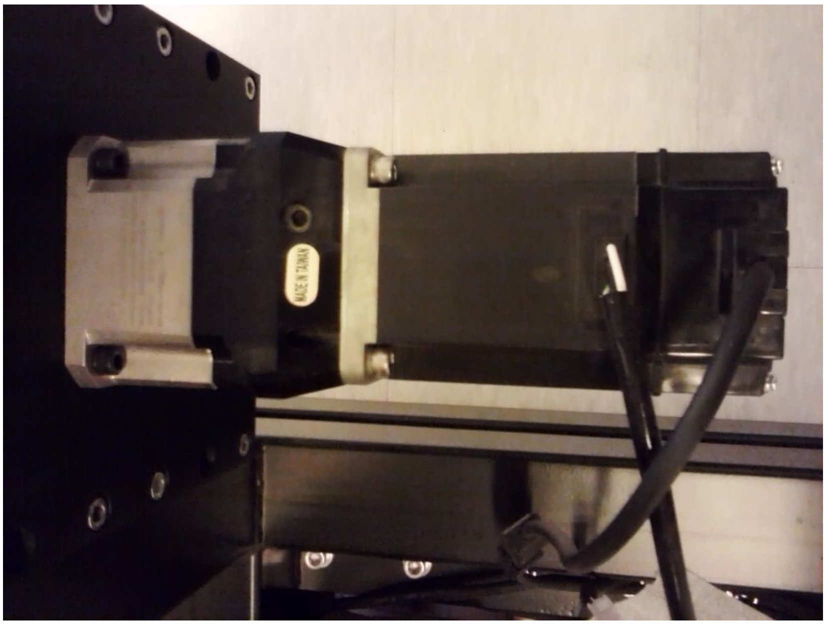


Figure 2.1 (c). Tension control of web before the master velocity roller.

Servo motor may be defined as a motor that is capable of delivering torque while at the same time giving feed back to the servo amplifier. The torque output of the servo motor is dependent upon the current supplied to it. This is determined by the servo amplifier. Feedback from the servo motor can be in many forms. It can be current or voltage output from a tacho-generator for velocity feedback, pulses from an incremental encoder for velocity feedback or digital signal from an absolute encoder or potentiometer for position feedback. Choice of feedback will depend upon the application. But incremental encoders known as quadrature encoders have become quite popular. Pulses produced by the encoder can be converted into velocity, position by the servo amplifier. Based on the command given to the servo amplifier and the feedback it receives, the control system in the servo amplifier determines current to be delivered to the servo motor. The servo motor and servo amplifier used in this work are HC-KFS73 and MR-J2S-70A, respectively as shown in figure 2.2.

(a)



(b)

Figure 2.2 (a) Servo pack MRJ2S70A and; (b) servo motor HC-KFS-73

Servopacks could be avoided by replacing the servo motor with an ordinary electric motor coupled to a feedback device and the servo amplifier with a power inverter. Servo packs are preferred in industries as well as laboratories due to several advantages. Firstly the servo packs come equipped with built in safety features that prevent damaging situations to both the motor as well as the equipment, such as over current, over velocity, excess vibration to name a few. These may be implemented from scratch for a custom built system but will require low level implantation, and is as such beyond the scope of this work. Commercial servo-packs have advanced to the point where practicing engineers need little knowledge of control engineering to implement complex automation tasks. For a standard motor torque is not a linear function of current but the servo packs handle the linearization and we need only provide an analog signal to the servo pack and torque is a linear function of this signal. One of the widely used servo pack types in converting industry has simultaneous torque and velocity control mode. Wherein, the velocity is controlled subject to a torque limit and vice versa. In feedback control one of the parameters-velocity or torque- is used as the control parameter, while the other is set as a multiple of the initially set parameter. The multiplication factor is usually set as a constant by the practicing engineers based on their experience. As to which parameter among velocity and torque are to be used as control parameter and which as limiting parameter is a topic under debate by practitioners. In this work torque control with velocity limit has been used in all the servo motors in the experimental setup. Which implies that torque varies linearly with respect to input to servo pack which is -8 to +8 volts (-1200to +1200 N-m) and input velocity limit is-10 to +10 volts (-3000rpm to +3000 rpm). Mitsubishi brand servo-amp (MRJ2S70A) and servo motor (HC-KFS-73) were used.

2.1.2. Load cells

Tension in a span is measured with the help load cells. Load cells provide feedback to the tension control system. The load cell is essentially an elastic structure that deforms linearly corresponding to an external load with in prescribed load limit. Deformation in an ideal load cell should be minimal but is unavoidable as the load is measured from the deformation. Deformation of the load cell is measured using a precise strain gauge. A half bridge strain gage present in the load cell is used to measure the strain. Load cell used has capacity to measure loads up to 50 lbs. This equates to approximately 250 N. The load cell is cantilever type and has a mechanical stop to prevent breakage of the device under overload. Also the relation between the strain and load is linear within the rated load. This implies that the resistance output from the strain gauges is also linearly related to load. Hence linear scaling of the resistance measured can be used to calibrate the load cell within the software. The load cell used for this work is shown in fig 2.3.

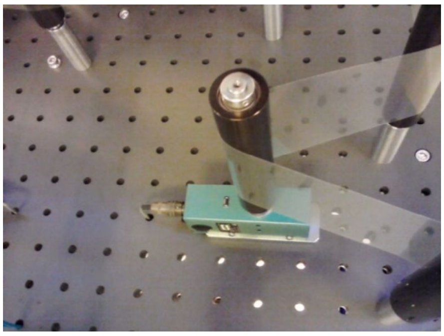


Figure 2.3. Cantilever type load cell

2.1.3. PXI system

PXI is a rugged PC-based platform for measurement and automation systems. It may be called an industrial PC. PXI follows an open industrial standard governed by the PXI Systems Alliance (PXISA). In this work the National Instruments (NI) PXI-1042Q chassis and NI PXI-8110 embedded controller have been used. Physically the PXI system is a chassis that can house a controller and a variety of cards. The controller is the PC part of the PXI system. PXI chassis can accommodate a number of cards in them depending on the model. The cards follow the PXISA standards. These cards interface with the PC. There are a variety of cards available in the market that can convert signals following a plethora of protocols and communicate with the PC, like TCP/IP, PROFIBUS, RS-232, IEEE-1394, motion control etc. Thus allowing a single system to process digital, analog, audio, video and many more types of signals and produce outputs as needed. This construction allows flexibility and at the same time the construction is rugged. PXI standard allows for real-time communication of data with PC.NI also provides a windows based software called LabVIEW. This software interfaces with the PXI cards. Programs can be written using this software that run on the PC. Programming code used in this software is known as G-code. It is a graphical programming language similar to that used in programming Programmable Logic Controllers (PLC's). Block diagrams that perform different tasks on the acquired data are wired together in specific sequence to perform the required computation on the data and the output is again communicated via the PXI cards.

NI provides PXI cards that can communicate with external expansion chassis. These chassis can hold a number of modules. Essentially these expansion chasses digitally communicate with the modules. Modules on the other hand are versatile. Depending upon the type it can be used to produce or receive digital or analog signals. There are also special purpose modules, such as that for load cells, accelerometers etc. This greatly simplifies the task for interfacing. Each module can have different sampling rates, built in filters, signal conditioning units etc. LabVIEW has provision for communicating with each individual terminal on the module. Further there are PXI cards with FPGA chips embedded in them. These can perform some simple computations on the card itself without relaying it to the PC, such computations are usually around three orders of magnitude faster than that done on the PC, and are hence usually used for processing signals from encoder. Schematic representation of data communication within the PXI system and the interface equipment is shown in figure 2.4.

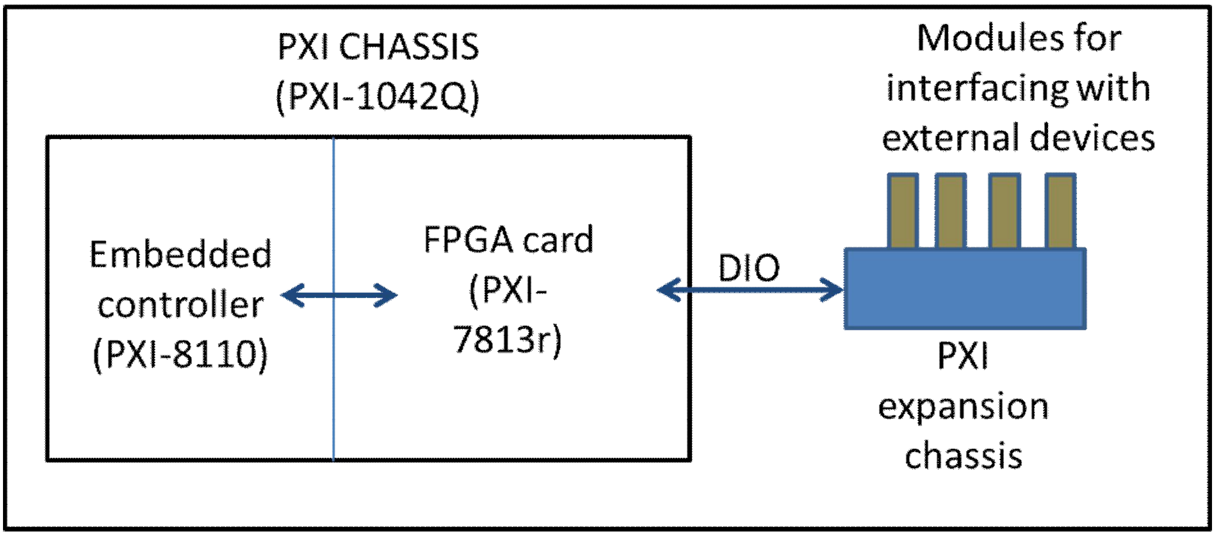


Figure 2.4(a). Communication within PXI system

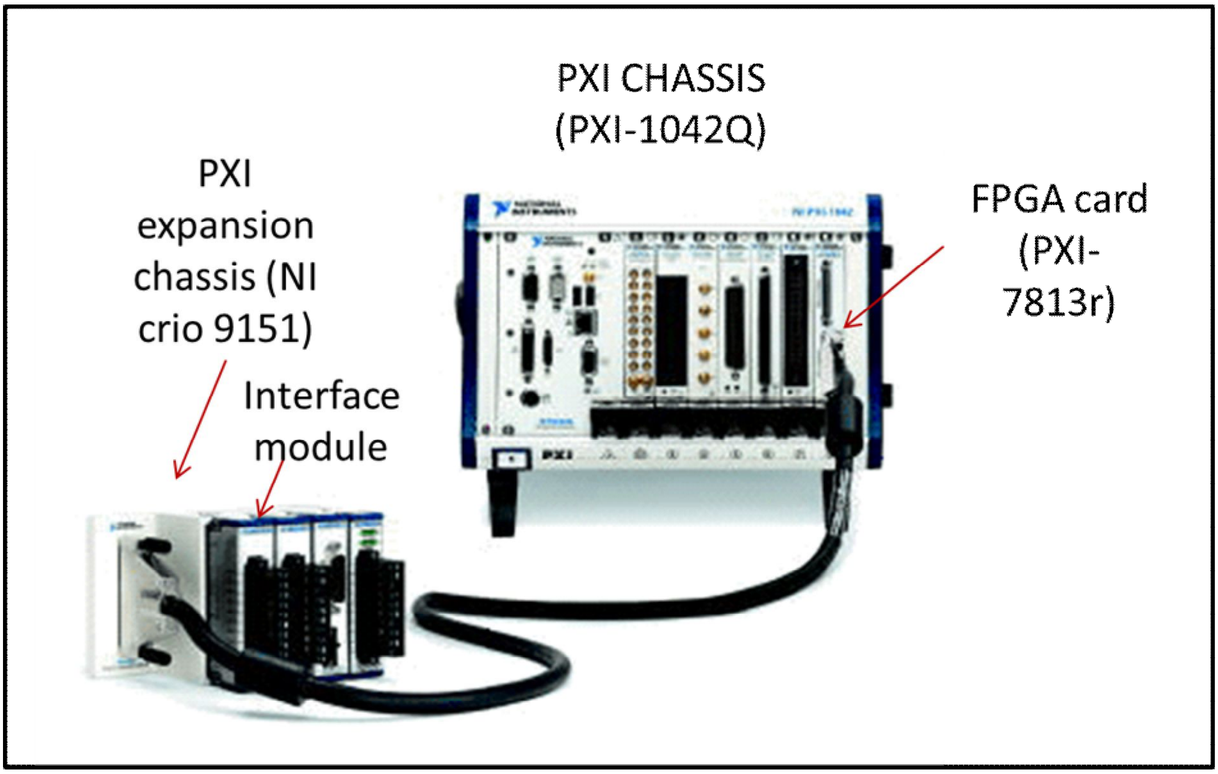


Figure 2.4(b). Hardware used for interfacing

2.1.4. Rollers and spindles

There are a number of rollers and spindles on the R2R system. As explained earlier the R2R system has two types of roller the driven rollers and the idle roller. Further there are driven spindles that hold the rolls and un-wind and re-wind sections. All the different types of rolls and spindles in the given system are shown in figure 2.5.The driven rollers in the R2R system are nip rollers they actually come in pairs, and engage with each other with the web between them. These rollers have a soft surface because the rollers engage with each other and also to improve traction with the web. The material on the surface is usually synesthetic rubber. The core of the roller is made of steel and is supported by bearings. In the nip roller pair only one roller is driven by the servo pack, the other roller is rotated by the driven nip roller. The engagement between the nip rollers is usually done by applying pneumatic pressure. But in this case the assembly of the idle nip roller is heavy enough to allow a satisfactory engagement between the driven and idle nip rollers. Servo motor is not directly coupled to the driven nip roller; rather a flexible coupling is used to account for any misalignment between the roller and motor axis. The nip rollers have a suitably large diameter to allow a sufficiently large velocity of the web. In this case the nip rollers are 80 mm in diameter, which will produce a maximum velocity of 0.4 m/s. Offset printer has a diameter of 160mm which gives a maximum velocity of 0.8m/s, but the smallest diameter driven roller in the R2R system determines the limiting velocity of the system with same servo packs. The diameter of roller is crucial in the design phase because there are speed limits in a servo motor. There is usually a tradeoff involved because as we increase the diameter the velocity increases but so does the inertia of the rollers which usually leads to poor control characteristics. Idle rollers on the other hand are designed to be as small and light as possible to prevent the dynamics of their inertia from affecting the system performance. There again we have another tradeoff. Often in a multi-span R2R system the web has to take a very convoluted path, and during these sharp turns of the web path the web assumes the radius of curvature equal to that of the roller. Since the R2R system is designed to print electronic components very small radii of curvatures can be pernicious to the electronic circuits printed on the PET substrate.

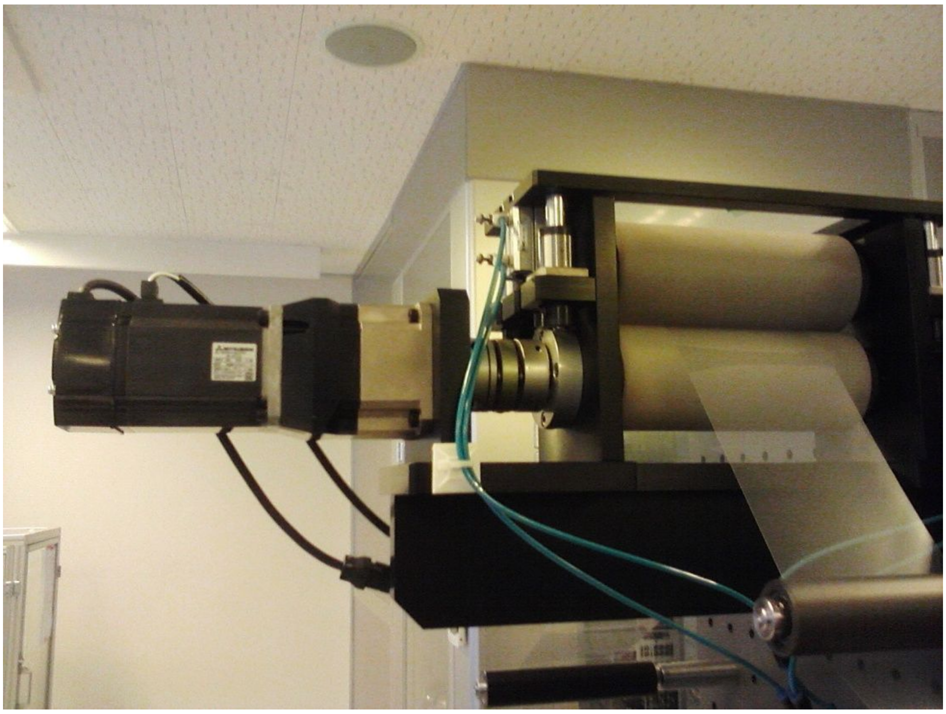


Figure 2.5(a). Nip-rollers used in the R2R system

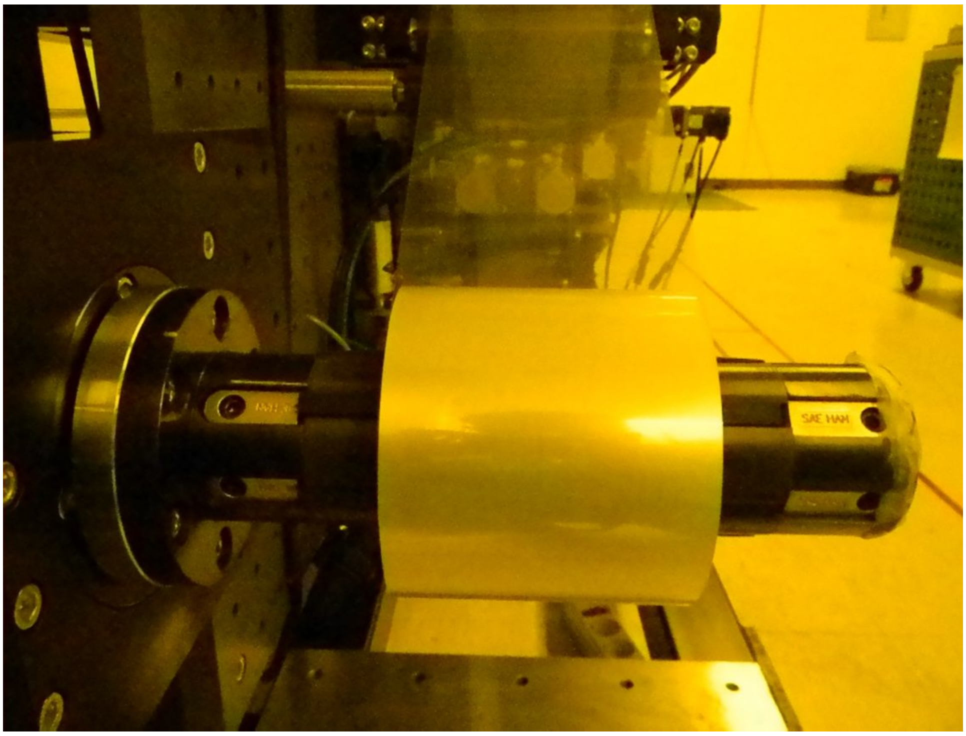


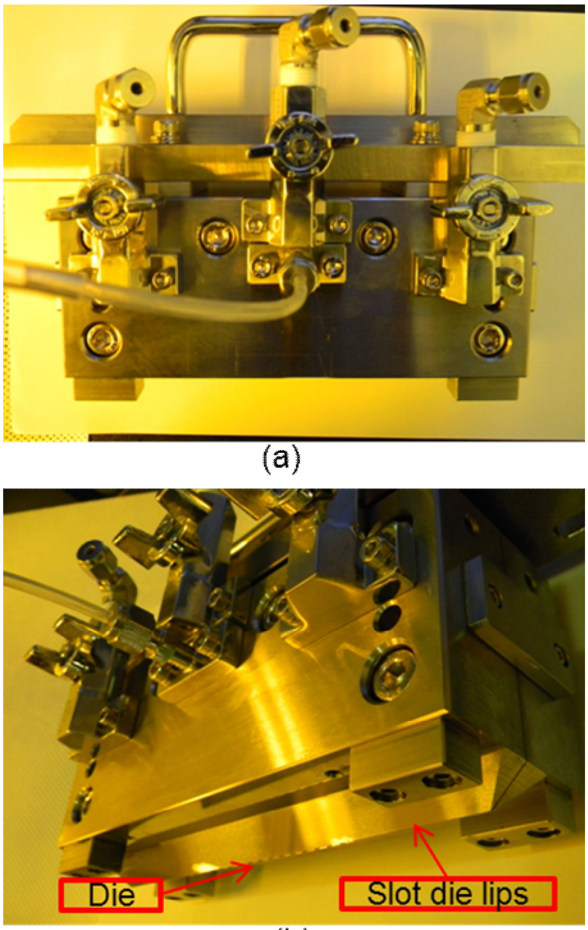
Figure 2.5(b) Expanding spindles

Spindles in this thesis refer to mandrels that hold the PET substrate rolls. These spindles are driven by servo packs via coupling, and are used in the un-wind and re-wind section of the R2R system. Purpose of using these spindles is to easily fix and remove rolls from the R2R system. Mandrels have expanding grips that engage with core of the rolls. Pneumatic pressure is applied to ensure perfect fit. Often in converting and printing industries the un-winder is not driven but rather a pneumatic brake is coupled to it to maintain a tension on the web in un-wind section. This practice is not suitable because large tensions are not acceptable in printed electronics. Instead a servo motor is coupled to allow better tension control.

As mentioned earlier the Offset printer is also a driven roller, but the dynamics involved are complex and require considerable attention, hence it is dealt with in detail in a separate section devoted to offset printing.

2.2. Slot die

Slot die is one of the simplest coating methods in existence. The slot die used in the R2R system is shown in figure 2.6. It is worth noting that slot die is just a precisely machined ink dispensing unit. Essentially the slot die dispenses ink uniformly on to a very precisely machined die. A complete Slot die system is typically made up of three distinct parts. The first is the slot die body. This is a precisely machined cavity that holds the die. Also there are air venting valves to remove the excess air form the die body. The second part is the die and the third is the ink pump. Slot die is shown in figure 2.6.



(b)

Figure 2.6.(a)Front view of slot die;(b) Isometric view of slot die

The surface tension causes the ink to flow along the surface of the die. Web is moved at a constant rate at a constant tension underneath the slot die. Due to close proximity of the die lip to the web, the ink flows from the die on to the web, and the stripes of ink left on the web are same as the shape of the die. One important parameter that controls the quality of coating besides web tension and velocity is the gap between the die and the web. This gap is adjusted with the aid of power screws shown in figure 6. One of the reasons this process is preferred in coating over others is that it is a non-contact process wherein the thickness of the coating can be controlled very accurately and the process renders itself to mass production. Besides this process does not affect the R2R system control because the process does not affect the R2R system dynamics.

2.3. Offset printing

Offset printing is a process of choice when the precision of the patterns and mass production capabilities is a concern and printed electronics requires both these qualities. Offset printing is a contact printing process. Which means the printing device comes in direct contact with the web. Every offset printer has three important components-gravure roll, offset roll and impression roll. There is another similar process that is a little less complex known as the gravure printing, but the offset printing is more precise than the gravure printing. Another related process is the flexographic printing. The commonality between the three processes is that the desired pattern is first engraved onto a hard surface. The hard surface can be plane or cylindrical. Of all the three processes gravure printing is the simplest. In this method the pattern etched on the gravure surface is the mirror image of the desired pattern, because the pattern is directly applied to the substrate (material to which the pattern is to be printed). It is crucial that the substrate be softer than the gravure because pressure is applied to help transfer ink. This method is used often in graphical printing industry to print upon paper and plastic films. Also it has been applied successfully in printing electronic circuits where the precision required is not much. Flexographic involves making protrusions on the printing rolls such that the ink is only on the protrusion. This method is precise but requires very sophisticated ink transfer mechanisms.

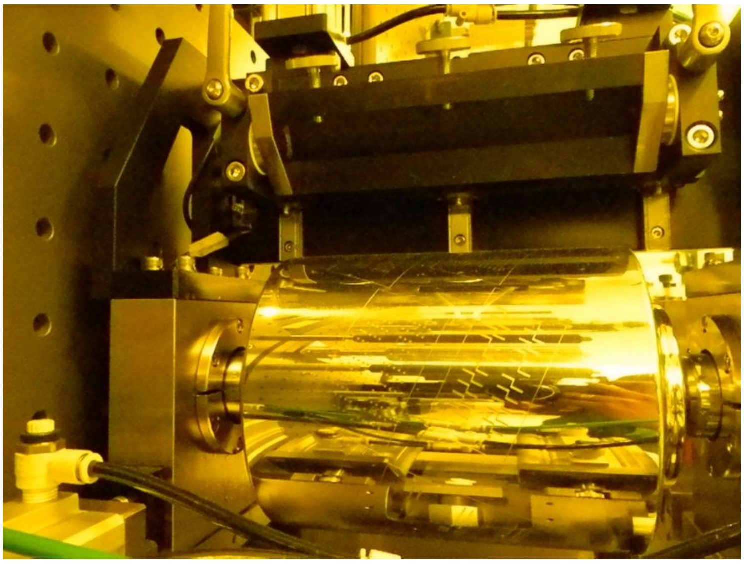


Figure 2.7 Gravure roll used

As explained earlier gravure offset printing (also known as offset printing) is one of the most precise printing techniques in existence. In this work the gravure offset printer has been used and is intended to be applied with the R2R system. The gravure offset printing can be explained as follows. The gravure roll is engraved with the pattern to be printed. Originally this process was developed for printing on uneven surfaces; hence the gravure would actually be a plain surface. This was changed to a roller for mass production of prints for graphical printing requirements. The gravure roll used here is shown in figure 2.7 . Gravure rolls are made in a number of ways. Usually a well ground copper roll with a steel core is used as the starting material. On this surface the engraving is made to resemble the desired pattern. Usually the desired pattern is not made as it is, if so then the gravure is known to have intaglio pattern. For fine printing requirements as is required in printed electronics the desired pattern is broken down into smaller sections called cells. The cells are actually pits that hold a predefined amount of ink. This approach is known as gravure printing. The reason that gravure engraving is used is to make sure that the amount of ink transferred to the substrate can be controlled to a greater degree than the intaglio printing. Also the uniformity of the final pattern can be ensured by creating cells. These gravure cells are generally created by three methods:

- Laser engraving.
- Electric discharge machining (EDM).
- Diamond stylus engraving.

In laser engraving a laser creates the necessary cells by moving along the pattern area, the cells may be created in single pulse or in a series of pulses. Laser engraving does not guarantee accurate cells structure. Also removal of material from cell does not take place. EDM is a process very similar to the laser engraving but is very efficient in removing the material that is engraved out of the cells. In this process an electric arc is struck between the gravure roll surface and an electrode. A fluid is passed to cool the gravure surface as well as to remove the engraved material. This allows creation of better cells. Since the material from the cells is removed instantaneously protrusions are not formed around the cells as is usually the case with laser engraving. The third popular method of diamond stylus engraving produces the best finish of all the three processes. In this method the cells are formed of diamond tips shaped in the form of the desired cell shape. The diamond stylus is impinged on to the gravure surface. This method still leaves material behind as the stylus merely displaces the material from the cells into the surrounding. Following the engraving process the gravure surface is chrome plated and finally polished to have a mirror finish.

2.4. Electro hydro-dynamic/electro spray deposition (EHD/ESD) system

EHD and ESD are processes for fine patterning and coating respectively. These techniques are currently being developed for application in printed electronic industry. But for mass production of printed electronics it is essential that these be implemented in an R2R system. It is crucial that these methods are implemented on an R2R system.

Basically EHD is the process of applying as strong potential drop between a nozzle containing ink to be patterned and the substrate. The ink in the nozzle is already maintained at a pressure. The electric field causes the ink to flow down to the substrate. The flow can be either in the form of droplets or in the form of a continuous jet depending upon the type of electric field applied-pulses or D.C. One of the key aspects of this technique is that the final pattern can be as small as 1/80 of the nozzle diameter. This allows for very fine patterns. ESD almost the same as EHD only that the distance between the substrate and the the nozzle is much larger and the jet splits into a fine spray.

EHD process is regarded as the future of printed electronics. But they come with a tradeoff. EHD process requires that the nozzle be moved along the path of the desired pattern. This presents a bottleneck to the R2R process. While other R2R processes work at the same pace as the R2R system this method is highly dependent upon the pace of the process itself which is extremely slow. The EHD system is shown in figure 2.8. Basically the EHD system can be likened to a CNC machine with 3-axis. The machine moves the nozzle in the X, Y and Z axes. The X and Y axis allows the nozzle to make patterns on the substrate while the Z axis is meant to adjust the gap between the nozzle and substrate so that the process may occur. ESD process also presents a bottleneck in that it may require several passes before a coating of required thickness is achieved. Both these processes slow down the whole R2R system if they are required for creation of an electronics device. For EHD system it is crucial to stop the R2R system completely so that the patterning may be completed. Thus the R2R system has to stop at regular intervals for the patterning and then restarted. R2R system startup and stop are usually not very smooth and is definitely time consuming. Therefore the system cannot run at high speeds.

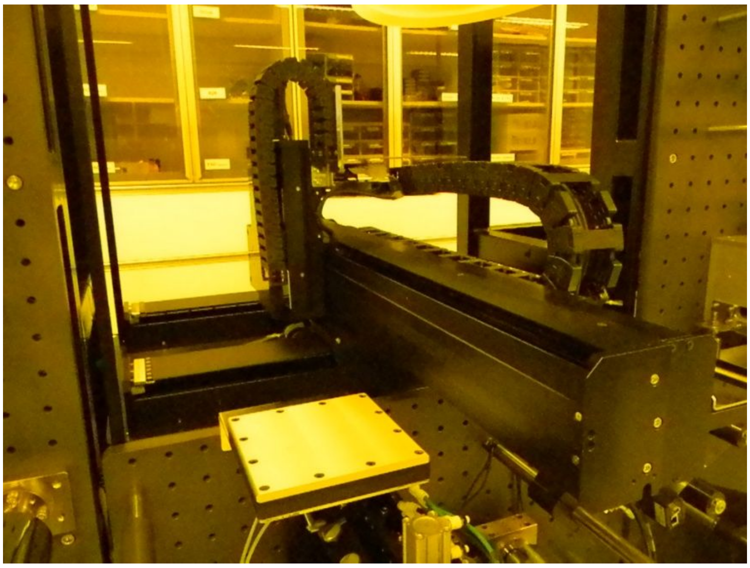


Figure 2.8. R2R based EHD system

This thesis deals almost exclusively with web tension control under different processing techniques, although lateral and longitudinal registration also is affected by poor tension control. Fuzzy logic has been used as a means to implement the control strategies, to allow swift control system design. A model based controller has also been implemented but the model was built only for augmenting an existing fuzzy controller.

2.5. Literature survey

The literature pertaining to web handling is vast but is spread across several decades. The progress in literature is also relatively slow due to saturated nature of the field. Literature in control of R2R system is even scarcer. Significant advances in drives and electronic controls have taken place only in the last decade. But as and when new processes are introduced to the already vast list of R2R processes the new literature begins to emerge. Printed electronics is a field which needs to merge with the R2R processing techniques in order to mass produce electronics at affordable prices. This has been considered for a while, but is yet to be a fully realized. Advances in embedded computing technologies like FPGA and multicore parallel processing have allowed the use of more computation intensive algorithms such as genetic algorithm(Tran et al., 2011) for control of R2R system.

2.5.1. Tension control

Web tension control has been extensively studied. Since multi-span R2R system is a time varying nonlinear system it is often studied using some nonlinear control theory. Even in nonlinear control theory the problem is often solved by linearizing it. This section of literature review is exclusively dedicated to web tension control. Since web tension control is a very old subject and a lot of literature has been published on the subject in the past few decades, this work focuses on relatively recent work, especially in the past decade. This is because; in the last decade digital industrial computers and microprocessor based drives have come into extensive use in the industry, starting a new era in R2R based industries.

Ku Chin Lin (Lin, 2003)has proposed and implemented a method wherein a single span R2R system is operated without a direct feedback from the load cell. In this method he has used an observer to predict the web tension and use it as feedback for web tension. Although written in 2003 it is obvious from the goal of the paper that tension transducers-load cells- were expensive and possibly not long lasting, this warranted for a feedback free tension control system. Also noteworthy is the fact that implementing such a system would have required a computer that predicts the tension. Dynamic equation of tension has been derived from first principle. This equation is crucial to this thesis as well. Basically it relates the tension of the current span with the tension and velocity of the previous span.

…………….(2.1.1)

Where,

T_k (t)=tension in the kth span of the R2R system;

V_k=Velocity of the kth span as measured at the controlling roller of the span;

=Rk*ωk

Where, Rk= radius of the controlling roller of the span; ωk= angular velocity of the controlling roller.

L=length of the given span

C=spring constant of the web

Another significant contribution of [Lin, 2003]is the modeling of friction and inertia of the rolls. The roll radius is calculated as a function of initial radius and angular displacement. This radius is used to compute the moment of inertia of the rolls. Although [Lin, 2003] has derived the relation between tensions of adjacent spans, it does not use it, because the work has been implemented on a single span system. This creates a problem that can be easily linearized and is as such within the scope of solution within the frequency domain. The controller is in effect a PI controller with gains being modified as the roll radii change. Further the effect of roll eccentricity has been accounted for in the design. The final controller performance has been shown to be at par with the existing closed loop feedback.

A decentralized control system by [Pagilla et al., 2007], has developed for a multi-span R2R system taking into account the system model. The system model takes into account variation of roll diameter, and inertia. The experiments have been done on a large 3-span industry scale web handling system, in which the system is divided into three single-input-single-output (SISO) control systems. Equilibrium conditions have been applied to each individual span and the drive velocities and torques are computed. Finally the results have been proven to be better than the conventional PI controller.

Tension control has been dealt with in a number of ways in the past. [Weixuan Liu and Davison, 2003] have dealt with, using principles that are applied in servo systems. In their work a 2-span R2R system has been used. Besides the control approach the paper is very informative about the performance criteria that are generally followed in web handling. Some of these criteria are that web tension be set at 10-25% web yield strength and kept within 10% of this set point during run time and 25% of this set point at speed set point change. These criteria are off course for general web handling and may not hold good for all applications. A detailed study of these is done in section 3.3. [Weixuan Liu and Davison, 2003] also discusses the several potential methods to design tension controller such as SISO, MIMO and system identification along with their merits and demerits. Among these it is said that SISO is the easiest controller to design, but will lead to poor performance due to neglect of the interactions between the spans. MIMO is said to be effective but requires a very accurate system model which given the scale of the system is difficult to obtain. The controller in [Weixuan Liu and Davison, 2003] finally designed assuming that the system is linear time invariant (LTI).

[Okada and Sakamoto, 1998], [Weixuan Liu and Davison, 2003], was one of the first to apply a control method other than conventional control theories to the control of a web handling system. This work was purely simulated, but the simulation was done on a very realistic model of the system. The model featured most of the elements on a typical web handling system such as unwinder, draw roll, dancer and a rewinder. Also the web is modeled as a visco-elastic element which is hardly seen elsewhere. The most prominent part of the work was that the controller used was based on fuzzy logic. Fuzzy controller itself is simplistic (refer to section 3.1 for fuzzy logic jargon). Fuzzy input sets were triangular while the output is given by fuzzy singletons. Tuning of the controllers is done by modifying the output scaling factors. A fuzzy self-tuner changes the tuning parameter for each decentralized controller based on the performance of the system.[Sakamoto, 1999] discusses another simulation study that measures the interaction that exists between the different spans of a R2R system.

After a long gap in web tension literature another unconventional control approach was introduced by [Chen et al., 2004]. This work introduced the idea of applying Artificial Neural Nets (ANN) to R2R control for the first time. This paper features yet another realistic simulation based control system. The mathematical model has all the parameter variations that happen in the real system. The application of neural network is to account for the uncertainties and the un-modeled errors that exist in the system.

[Tran et al., 2011] and [Choi et al., 2011] have used back stepping control principle to achieve precise web tension control of a 2-span R2R system. Back-stepping may be regarded as the middle path between SISO and MIMO control approaches. In [Tran et al., 2011] have used back-stepping with modified genetic algorithm to obtain the optimal control of web tension, while [Choi et al., 2011] has just used back-stepping controller. It is worth noting that in this control approach the interaction between the different spans is taken into account but it regards the span prior to the controlled span. Further the back-stepping controller is also supported by the conventional control theories as it is designed to satisfy Lyapunov stability criteria. Genetic algorithm is a very efficient optimization technique which prevents any chances of convergence to a local optimal control solution. But due to the computational complexity of the method, in [Tran et al., 2011] it is done in simulation and applied to the real system.

Registration error is the error in the alignment between two consecutive patterns printed one on top of another. [Kang et al., 2010a] and [Yoshida et al., 2008], are the only ones to discuss registration control in recent times. Registration may be regarded as a separate field in printing controls, but is closely associated with tension control and lateral control.

[Imamura et al., 1999] have applied closed loop tension control of a filament winding system using feedback from a load cell. The controllers tested in this work are PID and I-PD. This is in effect a single span system.

[Knittel et al., 2001] have implemented a PID based feedback control of anR2R system. The contribution of this work is test with a semi decentralized gain scheduled control of a multi span R2R system. Nip rolls have been avoided in this work leaving room for web slippage. Also it is stated that a gain scheduling based controller is more effective in limiting the coupling between the tension and velocity control.

Accumulators are used in R2R processing lines that are very ling and have many spans with a variety of processes being done on the web. Under these circumstances it is essential that the process is stopped as infrequently as possible. Because if the R2R system stops it is difficult to restart all the processes and optimize the process parameters. But in most R2R systems the unwind rolls and rewind rolls have to be changed-as unwind roll exhausts and rewind roll is fully wound. The accumulator is a section that is added soon after the unwind section and just before the rewind section. Off course this applies only to low speed operation. Basically the accumulator is a collection of idle rollers, the distance between these idle rollers can be changed with the aid of a prime mover-usually a hydraulic cylinder that allows the idle rollers to change the web length within the accumulator. [Pagilla et al., 2001] have developed a simplified state space model of an accumulator taking into account the dynamics of tension, the accumulator set up and the pressure of the hydraulic cylinder. Further the model is tested in a real accumulator. [Pagilla et al., 2003a] has added to[Pagilla et al., 2001], the dynamics of the driven rollers in entry and exit of the accumulator. Further a closed loop stable controller has been proposed along with an observer for tension control. In [Pagilla et al., 2004] the system proposed in [Pagilla et al., 2003a] has been validated in an actual R2R system.

Dancers are yet another mechanical device used to both control as well as to measure the tension a span. Also during start and stop of the system they perform the crucial task of damping any vibration. Basically it is very similar to an accumulator because it functions by varying the span length. But the dancer system typically cannot release or withdraw as a large a length of web as an accumulator. The dancer is a prime mover driven system that can is used both in an active as well as passive sense. In its passive form, the dancer is an idle roller that is loaded with a constant force that tends to increase the span length by moving. The force for this motion comes from a dead weight, a spring or a pneumatic cylinder. When the tension in the web exceeds the force exerted by the force from the external source the dancer roll moves to reduce web span and vice versa. A transducer attached to the dancer roll can measure the motion and there by act as a tension transducer. In an active dancer system the external applied force can be changed to actually perform closed loop tension control. [Pagilla et al., 2003b], have used an active dancer system to reduce periodic tension disturbances caused by an eccentric roll. Three approaches have been followed to achieve this-PID based, internal model based and a linear quadratic (LRQ) optimal controller. The LRQ controller has been found to be better than the PID controller. R. [Dwivedula et al., 2006], have compared the performance of an active dancer, passive dancer and dancer free system. The results show that the active dancer performed better at reducing the disturbances than passive dancer followed by the dancer free system. G. Ponniah et al [PONNIAH et al.,2012] have used a new approach to controller design for dancer system. This method has been described in detail in section 4.

Roll eccentricity can cause fluctuations in tension. This is primarily due to variation of the linear velocity due to eccentricity although the servos can tightly control the angular velocity. Since the velocity and tension are strongly coupled, the tension tends to vary as a result of the eccentricity of rolls. [Shin et al., 2002] have measured the linear and the angular velocity of a roll with unknown eccentricity and have modeled the eccentricity. Finally the known eccentricity has been used to modify the angular velocity of the drive so that the linear velocity is constant.

Web tension is regarded as a very important parameter in determining the quality of products processed on the R2R system. [Lee et al., 2010a] have managed to control the thickness and roughness of patterns made by a gravure printer on a flexible substrate using an R2R system. It is proven that the surface tension of liquid on a substrate changes as tension is applied to it. This has an effect on the pattern as it controls how the ink spreads on the surface of the substrate. [CHOI et al., 2012] have done a similar study on the slot die coating process. The ink used was PEDOT:PSS on PET substrate.

2.5.2. Printing

[Mäntysalo and Mansikkamäki, 2009] designed and manufactured a transmission line and a patch antenna for 2.4 GHz ISM band. One test set was manufactured using conventional etching technique for a reference with a metal thickness of 17 μm. Two other test cases were fabricated using an inkjet-based printing technique that is described in more detail later in this paper. Printed patterns have thicknesses of 2.5 and 0.5 μm. This work evaluates the suitability of printed electronics in high-frequency applications. Insertion loss in the 60 mm-length transmission line was 0.1 dB higher in the case of the printed (thick) line than in that of the etched line. Furthermore, impedance matching bandwidth was almost the same in all antennas, although a small decrease in radiation properties was found.

A gravure offset printing system by [Lee et al., 2010a] composed of a roll-to-roll web-providing apparatus, a cup-type encapsulated doctoring blade, a flat gravure plate, and CCDs for line-width measurement has been devised for printing the electrodes of flat panel display (FPD) devices. This system may be characterized as a small experimental system capable of carrying out printing tests prior to using a huge gravure offset printing system for mass production. The conceptual design of this gravure offset printing system is focused on conducting the reliability accelerating test and on mimicking the huge mass-production printing process required for FPD parts such as plasma display panel electrodes.

The thesis by [Kulachenko, 2006] addresses two topics in mechanics of paper webs in printing press applications. First is the dynamic behavior of the travelling webs. Second is so called "fluting" after heat-set web-fed offset printing. A non-linear finite element formulation has been developed in this study for simulation of travelling webs. The results of the studies shows that for the tension magnitudes used in the printing industry the critical web speed lies far above those used today. Speed limitations are rather caused by ink setting and tension control problems. Fluting was explained as a post-buckling phenomenon due to small scale moisture variations developing during through-air drying.

A gravure offset printing process has been developed by [Pudas et al., 2004a] for Ag-filled polymer conductor ink. Pad printing and roller type printing have been used. Curing and electrical properties have been studied. A roller type of gravure offset printing has been used to evaluate the printing process and pad printing to print on the non-planar substrates. Based on differential scanning calorimetry (DSC) and resistivity measurements during ink curing, it was found that the ink had an optimum curing temperature of 140 ◦C. Square resistance of 300 and 150μm wide lines can be as low as 20 and 28mΩ/sq., respectively, for 7–8.5μm thick line. The minimum line width was 70μm. This minimum line width can be reduced with different ink solvents, but in this case the line thickness suffers and the square resistance increases, respectively.

The development of gravure-offset-printing and low temperature cofired ceramic (LTCC) technologies for the miniaturization of electronic devices and components is described in thesis by [Lahti, 2008]. The development work has been verified by several applications. Several aspects of gravure-offset-printing have to be optimised in order to make it suitable for fine-line printing and these have been addressed in the study with a focus on the printing inks and plates. Gravure-offset-printing inks were developed from commercial thick-film pastes. The effects of different ink characteristics on some properties of conductor lines, such as line width and resistivity, were studied. The dependence of the conductor lines on the quality of the engravings in the printing plates was also studied. The narrowest line widths obtained were about 30 μm with an accuracy of ±5 μm.

The gravure offset printing method was examined for the manufacture of thick-film conductors on alumina, using Ag based inks. In this research by [Pudas et al., 2004b], a roller type gravure offset manufacturing process was developed to give conductor lines and spaces down to 20 μm, together with a low square resistance. Novel hydrocarbon resin based inks have been used and compared to traditional ethyl cellulose based inks normally used in thick-film technology. The inks had a high viscosity compared to graphical inks due to their high solid content, which was necessary to enable a high printed mass. Different printing parameters were studied and printed sample properties were statistically compared. The results show that the cross sectional area of the lines is the best correlating measured property to describe the quality of the printing. 100% of the ink was transferred from the blanket to the substrate after 30 seconds. Prints from ink containing 85 wt.% of silver with optimized parameters resulted in a square resistance of 5 mΩ/sq. for 300 mm wide and 17 μm thick lines produced from a single print. These promising results are important requirements for high throughput electronics manufacture.

The reliability of gravure offset printing and presents a mechanism on how the width of the printed line increases on repeated printings is discussed by [Lee et al., 2010b]. Of the various printing process parameters, such as the resting times between doctoring, off, and set, printing velocity, printing pressure, and so forth, we investigated the effects of printing velocity, printing pressure, and blanket's thickness on the reliability of gravure offset printing. As the printing velocity increases, the reliability of gravure offset printing also increases. This is because the actual contact time between ink and blanket decreases, resulting in less solvent absorption into the blanket. Printing pressure does not have much influence on reliability. Even though some change was observed, it was within the range of experimental error. Under sufficient printing pressure, this observation implies that the more important factor as regards the absorption model is time rather than pressure. As the thickness of the blanket increases, the reliability also increases. In the case of a thin blanket, in particular, the reliability of gravure offset printing is sensitive to changes in thickness.

The inks used in gravure–offset printing are non-Newtonian fluids with higher viscosities and lower surface tensions than Newtonian fluids. This paper by [Ghadiri et al., 2011] examines the transfer of a non-Newtonian ink between a flat plate and a groove when the plate is moved upward with a constant velocity while the groove is held fixed. Numerical simulations were carried out with the Carreau model to explore the behavior of this non-Newtonian ink in gravure–offset printing. The volume of fluid (VOF) method was implemented to capture the interface during the ink transfer process. The effects of varying the contact angle of the ink on the flat plate and groove walls and geometrical parameters such as the groove angle and the groove depth on the breakup time of the liquid filament that forms between the plate and the groove and the ink transfer ratio were determined. Our results indicate that increasing the groove contact angle and decreasing the flat plate contact angle enhance the ink transfer ratio and the breakup time. However, increasing the groove depth and the groove angle decreases the transfer ratio and the breakup time. By optimizing these parameters, it is possible to achieve an ink transfer from the groove to the flat plate of approximately 92%. Moreover, the initial width and the vertical velocity of the neck of the ink filament have significant influences on the ink transfer ratio and the breakup time.

Polymer solar cells are reviewed by [Krebs, 2009a] in the context of the processing techniques leading to complete devices. A distinction is made between the film-forming techniques that are used currently such as spin coating, doctor blading and casting and the, from a processing point of view, more desirable film- forming techniques such as slot-die coating, gravure coating, knife-over-edge coating, off-set coating, spray coating and printing techniques such as ink jet printing, pad printing and screen printing. The former are used almost exclusively and are not suited for high-volume production whereas the latter are highly suited, but little explored in the context of polymer solar cells. A further distinction is made between printing and coating when a film is formed. The entire process leading to polymer solar cells is broken down into the individual steps and the available techniques and materials for each step are described with focus on the particular advantages and disadvantages associated with each case.

Since D flip-flop is one of the indispensable building blocks in integrated circuit (IC) design, providing a successful way to print D flip-flop on plastic foils will be the first step to reach fully printed flexible IC. Here, the network structure of single-walled carbon nanotubes (SWNTs) as an active layer has been employed to print the driver and load thin-film transistors (TFTs) of the D flip-flop by [Noh et al., 2011b]. The same physical dimensions of driver and load TFTs were first developed to fully gravure print the D flip-flop because of the advantage of tunable electrical properties of network density of SWNTs. Therefore, the circuit design and printing becomes simpler and more convenient than using general design rules. Furthermore, the SWNT network structure in the active layer can also minimize the fluctuation of threshold voltages (Vth) of SWNT-TFTs because of the use of the same physical dimensions in TFTs. The resulting gravure-printed D flip-flop shows a clock-to-output delay of 23 ms for 20-Hz clock signal. This is the first reported D flip-flop performance using all gravure-printing method yet achieved.

All-printed half adders will be the first step to the way of printing an arithmetic logic unit which will be further expanded to printing microprocessors directly onto flexible plastic foils by [Noh et al., 2011a]. In this letter, the half-adder circuit has been constructed using an all gravure printing process on poly (ethylene terephtalate) foils. To successfully operate the printed half adder, we first simulate the half adder using the parameters extracted from gravure-printed single-walled carbon nanotube (SWNT)-based thin-film transistors (TFTs) to provide a tolerable range of fluctuations of electrical parameters of the gravure-printed SWNT-based TFTs. Based on the close comparison between simulation results and attained electrical parameters of printed TFTs, controlling waviness of printed drain–source electrodes has been found to be a key factor for successfully executing the function of a printed half adder on the plastic foils.

A roto-gravure printing technique has been developed for conductive lines on paper and plastic films by [Pudas et al., 2005]. Rotary-screen-printing was used to make comparative prints. The inks contained metal particles in an organic medium and were cured in temperatures of 70–120 ◦C, limited by the substrate durability. The following conductor line properties were characterized for different substrates: resistance, yield as a function of line width, coil inductance, folding endurance, adhesion, printed antenna properties and maximum current density. A printed resistance down to ∼50mΩ was obtained, with conductor lines 4–7 μm thick. Minimum line

resolution and resistance were affected by smoothness of substrates. Adhesion properties were adequate for the studied components.

The gravure offset method has been developed toward an industrially viable printing technique for electronic circuitry. In order to obtain the optimum ink resin for printing lines of required thickness (5 μm) of narrow lines (down to 25 μm), several ink resin systems have been assessed in previous studies by [Pudas et al., 2002]. The best printed results were obtained with a novel ink using a hydrocarbon resin. This ink did not comply with the traditional ink transfer mechanism based on evaporation of the solvent, but with a postulated new "absorption mechanism."

[Lee et al., 2010a] show that the quality of a printed pattern (thickness and surface roughness) could be affected by tension variation of the flexible bare substrate in spite of the optimal settings of the ink, substrate, and printing method. In addition, an ink-transfer mechanism for the R2R printed electronics is analyzed to reveal the relationships between the dynamic surface roughness and tension of a moving web. Since the dynamics of the physical problem are complex, simple meta models using a design of experiment are developed. The experimental results are found to be in agreement with the meta models. It is found that the two important factors for achieving the desired thickness and surface roughness of the R2R printed patterns are optimal tension and control accuracy of the operating tension.

Ink transfer process from the printing roll to the web was investigated using a Computational Fluid Dynamics (CFD) technique for the roll-to-roll (R2R) printing application by [Lee and Na, 2010]. A parametric study was conducted to identify the effects of fluid parameters such as viscosity, surface tension and contact angle. To make the present analysis more relevant to the real printing system, a three-dimensional computational configuration for the commercial software was set up using the information obtained from the typical R2R system. Simplified one dimensional semi-analytic model based on Reynolds equation was compared with the CFD results to assess the validity of the results. Pressure distribution states that 1-D analysis is reasonably good in capturing the flow physics. The 3-D simulation with VOF (Volume of Fluid) shows that viscosity is the most important parameter. Moreover, the larger surface tension resulted in smaller amount of ink transfer.

In order to prepare a suitable substrate for printed electronics, the paper surface was modified by means of coating. PET foil, which has so far been used for this purpose, is not as broadly applicable as paper substrates. The advantages of paper lie in its broad application areas, price, process ability, register accuracy and environmental friendliness. It was possible to modify paper by means of coating in a way that applied functional polymers, like PEDOT:PSS, retain their electrical functionality. The sheet resistance of printed layers is now approaching sheet resistance values of PET foil (factor 2). An organic field effect transistor (OFET) with printed SD structures has been successfully prepared on the coated paper substrate by [Trnovec et al., 2009]

For the adaptation of the roll-to-roll printing method to printed electronics, it is mandatory to increase the resolution of the register control. Therefore, it is desired to derive a mathematical model for the register and to develop a controller to reduce register error. The mathematical model of cross direction register was derived considering both a lateral motion of a moving web and a transverse position of a printing roll by [Kang et al., 2010b]. The proposed mathematical model could be used to improve the performance of the cross direction (CD) register controller in a large area, roll-to-roll printing machine. The mathematical model was validated by numerical simulations and experimental verifications in various operating conditions using a multi-layer direct gravure printing machine. The results showed that the proposed model was effective in predicting the CD register in multi-layer printing.

Gravure, a printing process which offers the highest resolution, highest speed, and largest volume production in the graphic arts is demonstrated as a viable technique for printed electronics by [De la Fuente Vornbrock, A., 2009] in his thesis. In order to make laboratory-scale research with this technique possible, a custom table-top gravure printing press was designed.

This press allows for small amounts of ink to be utilized during a print and enables multi-layer

prints with a registration accuracy not seen in conventional gravure printing presses and suitable for printed electronics. With this press, printing processes to deposit functional materials for printed circuits are investigated with a focus on developing process modules to manufacture fully printed organic thin film transistors. Considerable effort is made to establish processes to deposit metallic lines with feature sizes below 20 μm and a total surface roughness below 20 nm, uniform thin films of polymer dielectrics with thicknesses as low as 70 nm, and high performance polymer semiconductors. These processes are then integrated to manufacture capacitors suitable for integrated circuit components and organic thin film transistors with operating frequencies as high as 18 kHz.

[Reuter et al., 2007] report on results of investigating the material–process interaction for the case of offset printed conductive polymers. We interpret the characteristic branched morphology of printed layers of Poly (3,4-ethylenedioxythiophene) doped with Poly(4–styrenesulfonate) in terms of the phenomenon of "viscous fingering". A comprehensive study of the relevant process parameters reveals that the conductivity of the printed layers results from an interplay between the characteristic wavelength of the fingered structure and the deposited amount of material. Furthermore, optimization of the process parameters allows for significant reduction of the sheet resistance for about 1 order of magnitude to 0.5 kΩ.

[Lee et al., 2010b] found that a printed pattern geometric quality which affects functional quality of printed electronic device could be changed with respect to operating tension of bare substrate even if local optimized ink, substrate, and printing process were applied. Additionally, ink transfer mechanism for R2R printed electronics is analyzed regarding a dynamic surface energy of a bare substrate under a tension in R2R printing systems. With the aim of an efficient prediction of the thickness of R2R printed patterns for given operating conditions, a simple meta-model is developed by using the design of experiment (DOE) method. Also, the proposed meta-model has been verified by several experiments. Through the results, it is presented that how to find an optimal operating tension in R2R printed electronics for guaranteeing a required thickness of R2R printed patterns.

[Ahmed et al., 2011] examines the transfer of a non-Newtonian ink between two parallel plates when the top plate is moved upward with a constant velocity while the bottom plate is held fixed. Numerical simulations were carried out using the Carreau model to explore the behavior of a non-Newtonian ink in gravure-offset printing. The volume of fluid (VOF) model was adopted to demonstrate the stretching and break-up behaviors of the ink. The results indicate that the ink transfer ratio is greatly influenced by the contact angle, especially the contact angle at the upper plate (a). For lower values of a, oscillatory or unstable behavior of the position of minimum thickness of the ink between the two parallel plates during the stretching period is observed. This oscillation gradually diminishes as the contact angle at the upper plate is increased. Moreover, the number of satellite droplets increases as the velocity of the upper plate is increased. The surface tension of the conductive ink shows a positive impact on the ink transfer ratio to the upper plate. Indeed, the velocity of the upper plate has a significant influence on the ink transfer in gravure-offset printing when the Capillary number (Ca) is greater than 1 and the surface tension dominates over the ink transfer process when Ca is less than 1.

Web deformation occurring in the ink transfer process from the printing roller to the flexible web was investigated by [Kim and Na, 2010] using a CFD technique for the application in roll-to-roll printed electronics. Analysis for the flow-structure interaction was conducted to assess the deflection and stress distributions of the web. To make the present analysis more relevant to the real printing system, both realistic geometric configuration and ink properties were set up using the information obtained from the typical roll-to-roll system. Fluid properties were found to influence to the shape of the transferred ink and the web deformation. As the line width becomes smaller than 100 microns, the appreciable distortion in the shape of the transferred ink occurred due to a relative importance of surface tension. Non-negligible web deflection occurs in all the cavity geometries considered in the present work but the ratio of the web deflection to the line width gets smaller as the printing pattern width becomes smaller. Thus, the surface and deflection will be important factors for the better printing quality under the 100 micron range.

In gravure offset printing, ink is transferred with the help of an offset material from a patterned gravure plate to a substrate. Thesis [Pudas, 2004] is concerned with the study and further development of this printing process for electronics; on alumina, glass and polymers. The work has been divided into five parts. In the first section, the printing process is described. The second section describes the composition of the inks for gravure offset printing and the resulting ink properties. It also presents the ink transfer mechanism; the model that explains how the ink is transferred between an offset material and a substrate. The third chapter details the printing process explained by a solvent absorption mechanism. The forth chapter describes the firing/curing of printed samples and their properties. The last chapter describes applications of the method. The inks used to produce conductors on ceramics (ceramic inks) and conductors on polymers (polymer inks) contain silver particles, and were under development for gravure offset printing. The major achieved properties were the high ink pickup to the offset blanket and high transfer percentage to the substrate. 100% ink transfer from blanket to substrate for ceramic inks and almost 100% ink transfer for polymer inks were obtained. The printing of ceramic inks was able to produce 8 μm of relatively thick, 300 μm wide lines with <10 mΩ/sq. resistance. The minimum line width for conducting lines was 35 μm, with one printing. Multi printing was applied producing as many as 10 times wet-on-wet multi-printed lines with 100 % ink transfer from blanket to substrate resulting in a square resistance of 1mΩ/sq. Polymer inks were able produce a square resistance of 20 mΩ/sq. for 300 μm wide lines after curing at 140 °C for about 15 min, and the minimum width was down to 70 μm. In the optimized manufacturing process, the delay time on the blanket was reduced to 3 s. In addition to ultra-fine-line manufacturing of conductors, the method enables the manufacture of special structures e.g. laser-solder contact pads with 28/28 μm lines/spaces resolution. With industrial printing equipment it is possible to produce 100 m^2/h with the demonstrated printing properties.

[Krebs et al., 2010] have utilized a combination of slot die coating and screen printing techniques on the R2R system to produce functioning solar cell. The interesting aspect of this work is that everything from fabrication, testing and finally packaging (lamination) is done on the R2R system. Also the cost estimate of production of solar energy from the given cells is made and compared to conventional energy sources and found to be at par. In [Krebs, 2009d] a combination of knife over edge coating, slot die coating and screen printing is used to fabricate a five layer solar cell. It is proven that this method leads to production of solar cells that perform ten times better than purely screen printed cells. [Krebs, 2009b] have made a clear distinction between printing and coating and has presented a review of some of the most prominent printing and coating techniques employed in fabrication of polymer solar cells. This paper also gives insight into the nature of the printing, advantages and disadvantages of the processes. [Krebs, 2009c] have used a copper foil as both the substrate and electrode for a solar cell. The only drawback of the process is that the method employs an R2R based vacuum coating (sputtering) technique.

2.6. Web tension controller based on fuzzy logic

Fuzzy logic is the logic that expresses variables (antecedent's and consequents) in all states in between yes and no. It has provided solutions to complex control problems in the past where conventional control methods have failed or have not been very efficient. Some of the most famous solutions given by this approach are, the inverted pendulum problem where an inverted pendulum has to be balanced, the cement kiln control problem, wherein the experience of a human operator had to be captured into a control equation. Fuzzy logic offers all the operations that conventional Boolean logic offers such as AND, OR, NOT etc. Tension control using fuzzy logic may be performed in two ways, T-S fuzzy system and Mamdani type controller. Mamdani type controller is the one that is more frequently associated with human like reasoning, because the experience of an actual operator is captured in terms of fuzzy logic. TS-fuzzy system is a system that takes in the system dynamic equations, converts state variables into fuzzy variables . A controller. In this thesis only Mamdani type controller has been used.

2.6.1. Fuzzy logic-introduction

As stated earlier fuzzy logic is the logic of the grey area. That is validity of a statement is not measured in yes or no (0 or 1), but rather in degree (0 to 1). It was originally invented to capture the data conveyed by spoken language and perform logical operation to come to conclusions from it. When interpreted as a control problem, it can be stated that the state of the system is interpreted linguistically and logical output is produced to control a given parameter. To perform these operations, the system state which may be measured in numbers like web tension, rate of change of tension, encoder pulse etc, have to be first converted to logical output such as low tension, high tension nominal tension etc. This is achieved by first converting a variable into fuzzy sets within the domain of the variable. These sets cover the whole domain of the variable and no matter what the state of a variable may be it will be a member of at least one fuzzy set. The degree of membership of a variable to a fuzzy set is measured by membership function. Most commonly used membership function is the triangular membership function. Other nonlinear membership functions such as Gaussian also exist. Desired output may be dependent upon more than one variable. Such dependence is captured by correlating the fuzzy sets of the influencing variables with the output through the logic operators. For instance if decision C will be the preferred outcome when two variables say, x and y are within the sets A and B respectively, then it can be said that

If A *AND* B *Then* C

Usually the final decision does not depend upon just one rule but a large number of such logic relations existing between the state variables and the control output. In that event all those rules are simultaneously executed and the final result computed by one of the defuzzification methods. Centre of gravity method is most frequently used for this purpose. After this step the

2.6.2. Input scaling

Input scaling is the process of first converting the raw input into the scale of the fuzzy controller. It also serves another purpose, often it is used to tune the controller. Scaling is done for numerical convenience. The domain of all the inputs is converted into a convenient scale such as (-1, 1) or (-100, 100). These domains allow easy division of the domain into fuzzy sets. This may be regarded as a form of standardization, because all the variables involved may not be within the same domain.

2.6.3. Fuzzification

Fuzzification is the process of converting crisp scaled data into fuzzy data. The fuzzification is done by using membership function. Each fuzzy set of a variable, is associated with a membership function. This function determines the degree of membership-0 to 1- of a variable to a given fuzzy set. As mentioned earlier these functions may be linear as in the case of triangular membership function or nonlinear as in Gaussian set.

2.6.4. Defuzzification

Defuzzification is done with the aid of a rule base which is a collection of If -Then statements. All the rules are simultaneously executed. One of the popular method of defuzzification is the center of gravity method. Detailed illustrations and equations of the process are given in section 4.1.

2.6.5. Output scaling

Output scaling is very similar to the input scaling. Output from the defuzzification process are typically in a standardaized range such as (-1, 1) or (-100, 100). This has to be converted to real world variable, such as analog signal to a servo pack. For this an output has to have the same range as that of the real variable. This also presents an opportunity for tuning the fuzzy controller.

2.7. Tension control-dynamics

Tension is controlled by controlling the torque in the servo motors that drive the driven roller. For tension of the span to be controlled the tension has to be measured and fed back to the controller. The controller has to produce a torque such that the tension is maintained. The rule base R2R system control system has to be defined such that it follows the tension dynamic equation in equation 2.1. The equation indicates nonlinearity and strong interaction between adjacent spans. Fuzzy logic is especially suited for this type of control. These dynamics equations give a good clue as to which rule bases will work.

2.8. Tension control guidelines

Tension control guidelines were established for converting industry keeping in mind adequate control. These were designed to account for a wide range of materials that are meant to be processed on the web handling machines, which will handle a wide variety of processes. TAPPI is one of the premier organizations in the field of converting and has set these guidelines to facilitate machine builder and converters. All the guidelines are introduced in section 2 [1.3]. These are not laws based on sound scientific basis; rather they are rules of thumb. Printed electronics is a relatively new application of R2R system. And since the substrate on which electronics circuits is printed will be without any tension when device is finally printed, it is obvious that least amount of tension be used while printing them.

3. Tension controller design and application

There are several methods to print on a flexible substrate. One of the broadest classifications is

- Contact printing
- Non-contact printing

Contact printing may be defined as any printing method wherein the printing tool or head comes in direct contact with the printed side of the flexible substrate. Some of the examples of contact printing are, gravure printing, gravure offset printing, flexographic printing, micro-gravure printing etc. EHD, ESD slot die coating etc. are non-contact printing methods. In this thesis greater attention is given to gravure offset printing which is a contact printing process. Two different algorithms that support this process are presented. Besides that slot die coating on R2R system have also been discussed.

3.1. Offset printing

3.1.1. Introduction

Web tension control is crucial to ensure quality of products that are produced in the form of web. Web may be defined as any product whose length is orders of magnitude larger than its width and width being orders of magnitude larger than thickness. In this paper the web used is made of PET (Poly Ethylene terephthalate) and is meant for use in printed electronics. In order for web to be processed a web handling system as shown in figure 3.1.1(a) is required. Figure 3.1.1(b) shows the schematic representation of the system. As shown, the web travels from un-winder, passes through the in-feed nip roll, followed by the offset printer, followed by out-feed nip roll and finally re-wound. The typical web handling system also known as roll-to-roll (R2R) system is made up of numerous servo motors and rollers. Rollers and rolls coupled to the servo motors are known as driven rollers and rolls respectively. In the equipment used for experiments in this paper as shown in figures 3.1.1(a) and (b), there are four driven rollers marked as in-feed, out-feed, gravure and offset rollers. Technically the gravure roller does not come in direct contact with the web but it does contribute to the force driving the web. Additionally there are two more driven rolls marked as un-winder and re-winder. The web in the form of roll is fixed on the un-winder and it travels through the in-feed and out-feed rollers before being rewound by the re-winder. Also there are numerous idle rollers which guide the web through the processing area. The length of web between any two adjacent driven rolls or rollers along the web is defined as a span. The tension in each of these spans has to be maintained precisely. Tension in this context is the internal tensile force setup in the web as a result of the motors torque acting on them. The tension in each span is measured with the aid of load cells. This tension information is captured by the data acquisition system called PXI. The PXI in turn relays this data to an integrated controller which is actually an industrial real time PC. The tension controller software running on the PC, computes an appropriate torque which is again relayed through PXI to the servo motor which is responsible for tension of a given span.

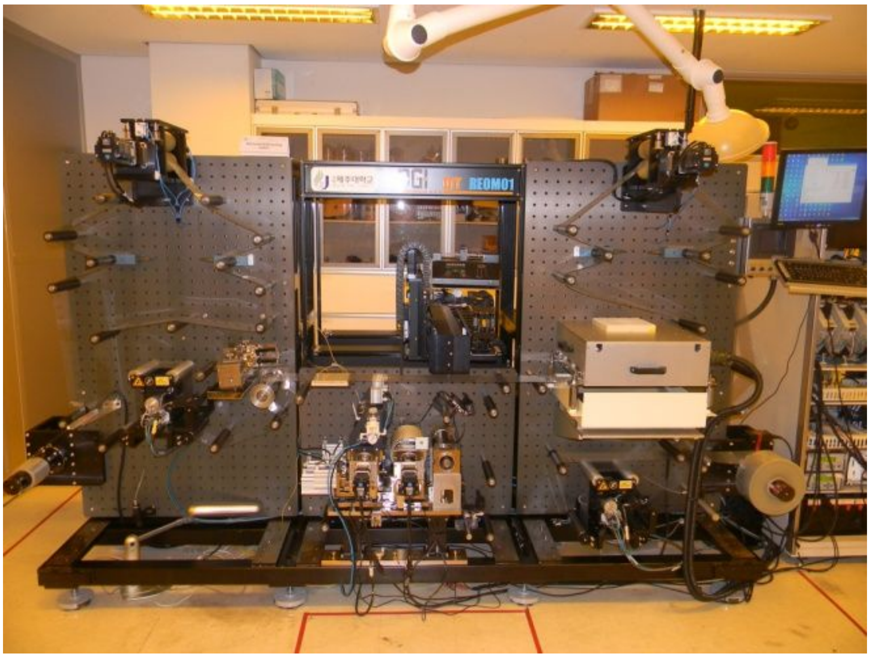


Figure3.1.1(a) Web handling system.

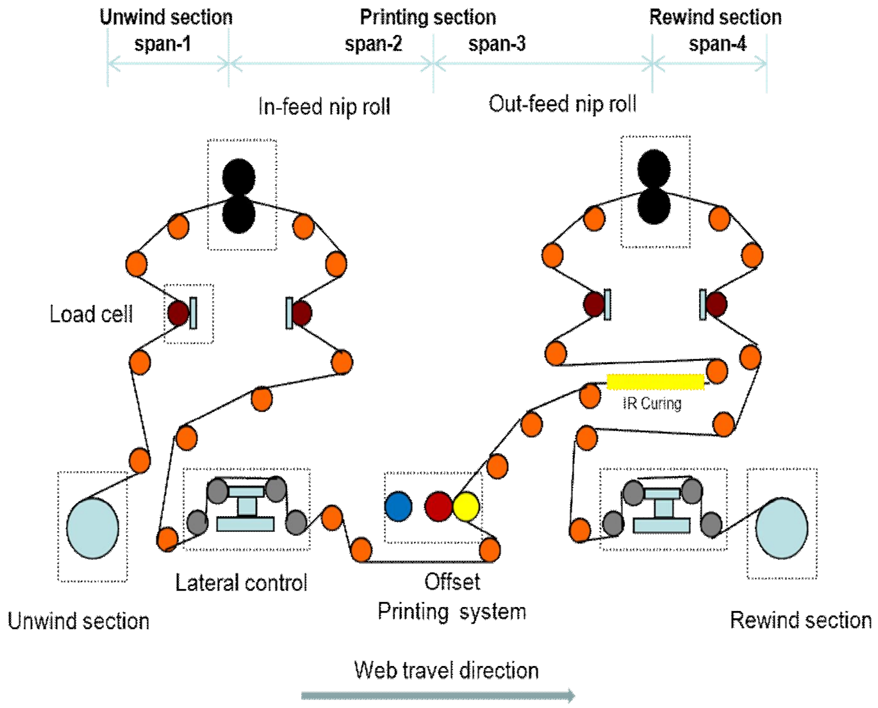


Figure3.1.1(b) Schematic representation of web handling system

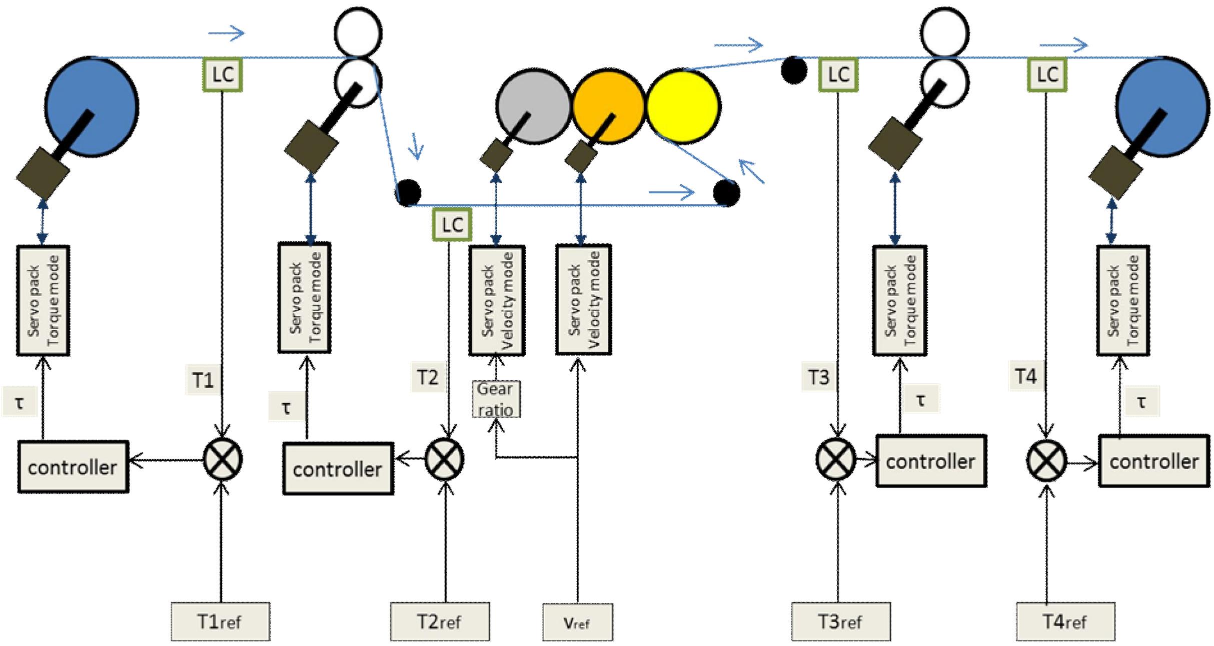


Figure3.1.1(c) Decentralized control architecture

Conventional decentralized control architecture is given in figure 3.1.1(c). In this approach the separate spans are controlled by separate controllers that take feedback from respective spans and thus we have a total of 4 spans as can be seen in the figure. In this architecture the velocity of the entire web is controlled by a master roller. In this case it is the offset roller(figure 3.1.2(a),(b)). T1, T2, T3 and T4 are tension in the four spans and T1ref, T2ref, T3ref and T4ref are their respective reference tensions as set by the operator, and master velocity is set by Vref. The controller is a SISO feedback controller, such as PID. This is the conventional control architecture. But the printing system used in this paper uses a different approach due to the difference of offset printer and the disturbances produced by it. Fuzzy logic is used to tackle the disturbances and this eliminates the necessity of expensive dancer systems. This work specifically deals with tension in process span-T2. This approach draws on the operator experience and experimental data, rather than system model thus removing the need to make an accurate system model. Furthermore the number of experiments needed to tune the fuzzy control system parameters are only few and this procedure has been elaborated in this paper.

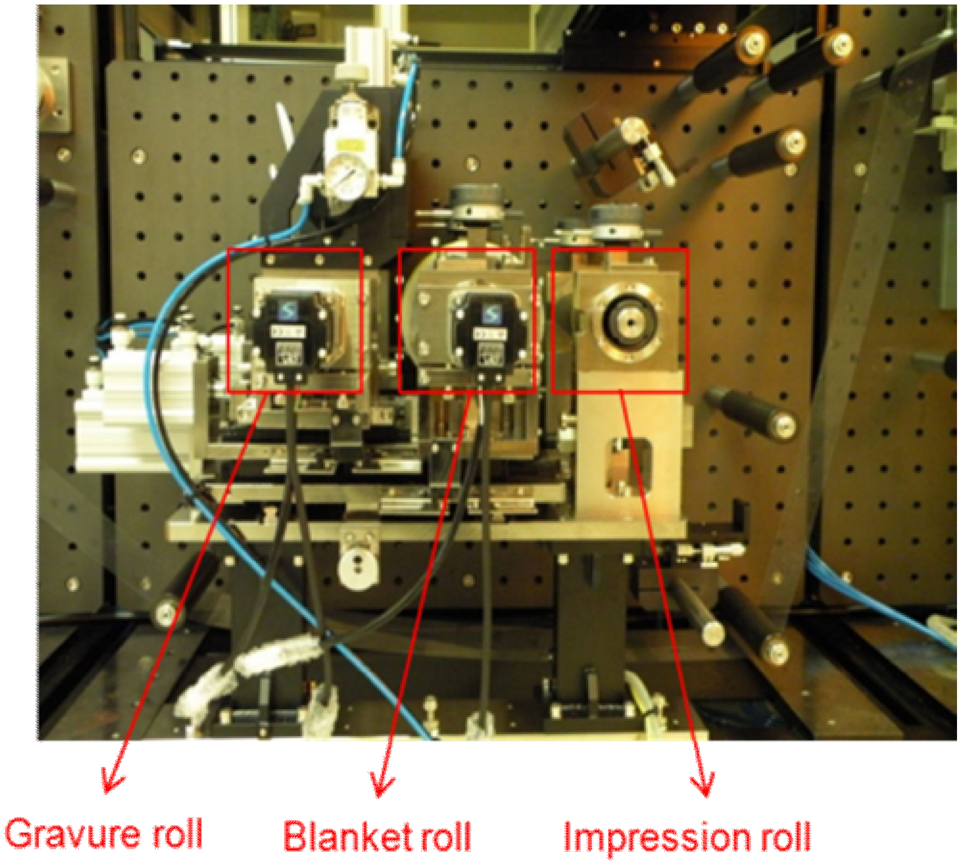


Fig 3.1.2(a). Offset printer-experimental setup

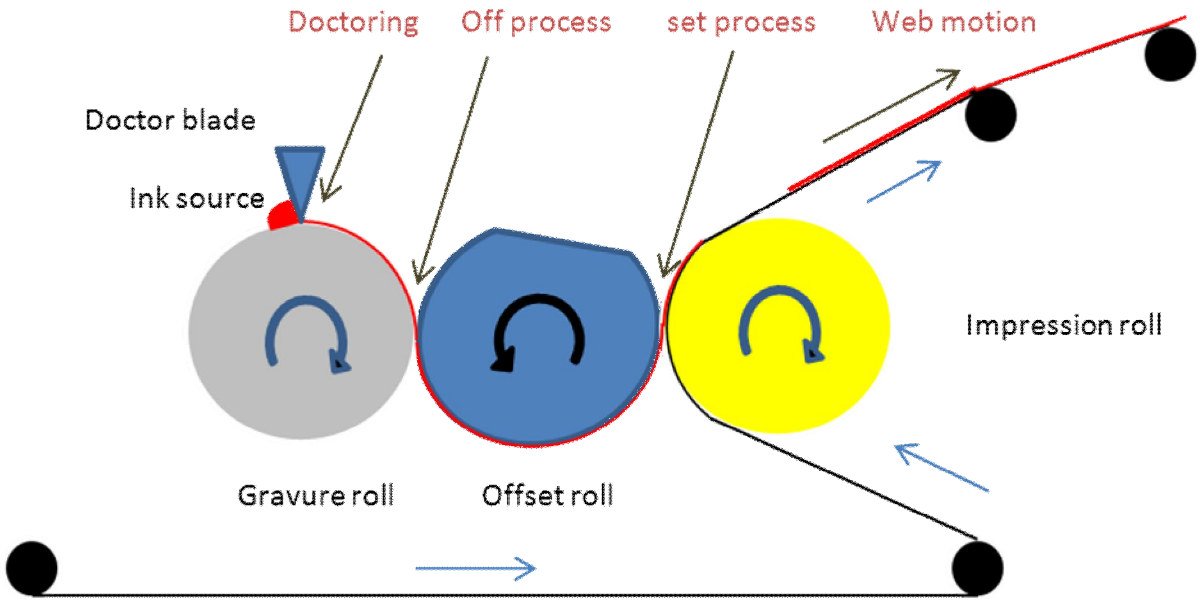


Figure 3.1.2(b). Offset printer-schematic representation with process description

3.1.2. Uniqueness And Disturbances Caused By Offset Printer

There is plenty of literature that address web tension and velocity control of R2R system but none that deal with tension control in an R2R system based offset printing system that operates on a continuous printing mode. This work specifically addresses the printed electronics industry. Although the converting industry – printing, packaging etc-is mature and industry standards exist they are practically useless in printed electronics. While the printing in the converting industry rely on aesthetic quality, the printed electronics require functional quality of the finished product. For instance the 10% of yield strength rule followed in the converting industry for processing tension cannot be applied in printed electronics, where minimal possible tension is recommended. The reason is that if a printed pattern is cured/dried at a high tension, damage can occur to it when the web tension is relieved after processing. These defects can be avoided by keeping the tension as low as possible, which in this case is 5N which is 8.3% of the recommended tension in converting industry. The normal industry practice is to use accurate velocity controlled gravure rolls to print; the tension control if necessary is left to dancer system. This approach is good but gravure offset printing has been known to have high printing resolution, due to the offset rolls ability to accurately pick up ink from gravure grooves. Offset printing may be classified in to two categories: continuous blanket system (CBS) and discontinuous blanket system (DBS), fig 3.1.2(b). Fig 3.1.2(b) shows the doctoring, off process, set process and movement of the web. Doctoring is the process of applying ink to the gravure grooves and removing excess ink. Off process is the process of the blanket on offset roll picking up the ink from the gravure grooves. CBS is simpler in construction and also easier to introduce into the R2R control system as it is similar to gravure printing and is smooth in operation because of the perfect cylindrical blanket roll. But the DBS as can be seen in fig 3.1.2(b), loses contact with the web at regular intervals. In set process the ink from the offset roll is deposited onto the web; the movement of the web also takes place simultaneously. During the start and end of a contact there is always some shock to the R2R control system. These shocks will affect product quality. But the use of DBS system is a necessity as registration control has become important. Further it is important that the blankets on the offset roller be replaced regularly, which is difficult in the case of CBS but convenient in DBS. In the DBS there is a non-contact phase in each cycle of operation between gravure and offset roll as shown in fig 3.1.3(a); this phase is used to correct registration error. Registration error is the error in the alignment between two consecutive patterns printed one on top of another.

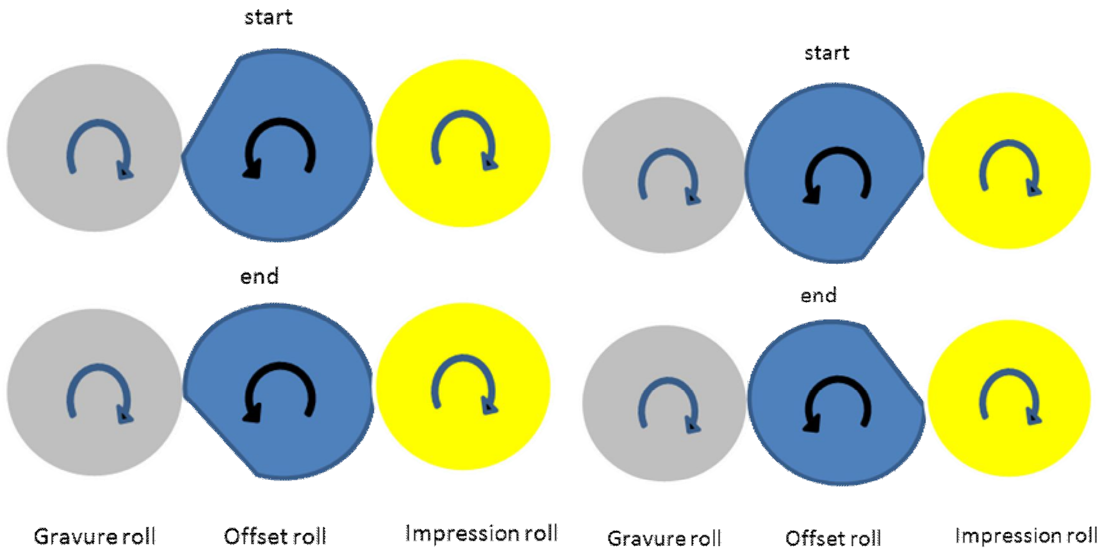


Figure 3.1.3(a) start and end states of Gravure-offset noncontact phase; (b) start and end states of Offset-impression noncontact phase

In conventional system the burden of moving the web falls entirely on the offset roller. When gravure roller is in contact with offset roller this load is shared. But during start of gravure-offset noncontact phase-fig 3.1.3(a)-the load on offset drive almost suddenly doubles causing the servo to overcompensate, causing spike in tension. In the same manner since other drives only control tension, the web begins to slow down in offset-impression non-contact phase-fig 3.1.3(b). Thus when contact is again restored there is a sudden acceleration which disturbs all the tension spans. To add to problems, the affinity between web (PET) and blanket (PDMS) is high, therefore the web sticks to blanket which at the beginning of offset –impression non-contact phase causes the plucking of the web. This is a big and unpredictable source of disturbance.

The aforementioned disturbances can be seen as described in figure 3.1.4, where one cycle of the system operation is shown marking some of the prominent features.

3.1.3. SERVO-PACKS AND OTHER EQUIPMENT

Commercial servo-packs have advanced to the point where practicing engineers need little knowledge of control engineering to implement complex automation tasks. For a standard motor torque is not a linear function of current but the servo packs handle the linearization and we need only provide an analog signal to the servo pack and torque is a linear function of this signal. One of the widely used servo pack types in converting industry has simultaneous torque and velocity control mode. Wherein, the velocity is controlled subject to a torque limit and vice versa. In feedback control one of the parameters-velocity or torque- is used as the control parameter, while the other is set as a multiple of the initially set parameter. The multiplication factor is usually set as a constant by the practicing engineers based on their experience. As to which parameter among velocity and torque are to be used as control parameter and which as limiting parameter is a topic under debate by practitioners. In this work torque control with velocity limit has been used in all the servo motors in the experimental setup. Which implies that torque varies linearly with respect to input to servo pack which is -8 to +8 volts (-1200to +1200 N-m) and input velocity limit is-10 to +10 volts (-3000rpm to +3000 rpm). Mitsubishi brand servo-amp (MRJ2S70A) and servo motor (HC-KFS-73) were used. Interface and control hardware are National Instruments products. The software was written in LabVIEW 8.6.

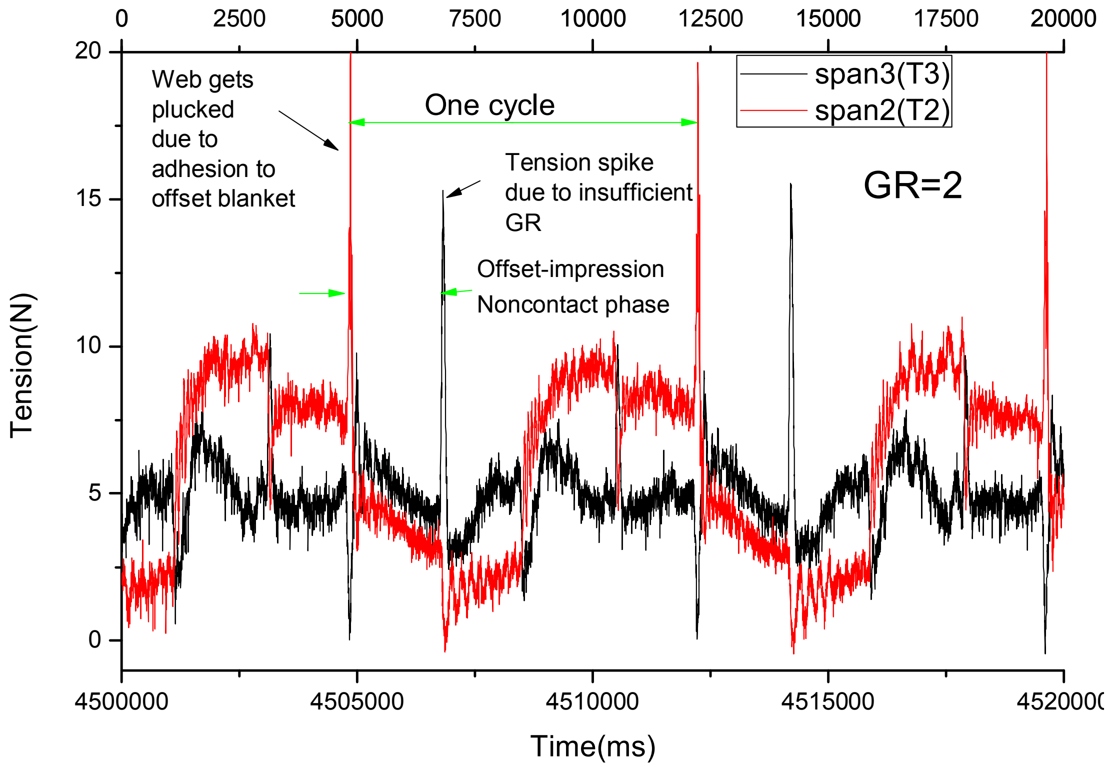


Figure3.1.4 system response: nomenclature of the various disturbances at GR=2

3.1.4. CONTROL SYSTEM DESIGN

The control system proposed here is meant to address some of the disturbances mentioned in section 3.1.2. Foremost a system that entirely relies on the offset roll for web velocity control as shown in figure 3.1.1(b) is infeasible in this context. Since the SISO tension control is an evolved field this paper deals exclusively with the design of control system for tension control in span 2, given by T2, the other tension spans in the system are controlled using simple SISO tension control. To accomplish this task the in-feed roll and the offset roll are operated as a pair of draw rolls. Draw roll control is typically used to control the strain of the web by giving different linear velocities to the two draw rolls on both ends of the span. But unlike a traditional draw roll, where a dancer system handles tension control-if at all it is used- in here the feedback from load cell is utilized, with the extent of draw being used to control the tension. The in-feed drive is also made responsible for velocity control. Hence the velocity will not change during Offset-impression non-contact phase. Assuming that dimension of offset and in-feed rollers do not change and as per [1.1] if their linear velocities are made equal and if their tensions of previous and the current span are equal, then the tension T2 will remain constant as given in eqn (1.1).

$$dT_k(t)/dt = (-V_k * T_k(t) + V_{k-1} * T_{k-1}(t))/L + C[V_k - V_{k-1}]$$

……………(3.1.1)

Where, T in T_k is the tension of a span and subscript K denotes the span number counted from un-winder; V_k is the velocity of K_{th} web span which is measured as the linear velocity of the downstream driven roller of the K_{th} span; L is the span length, and C is the spring constant of web.

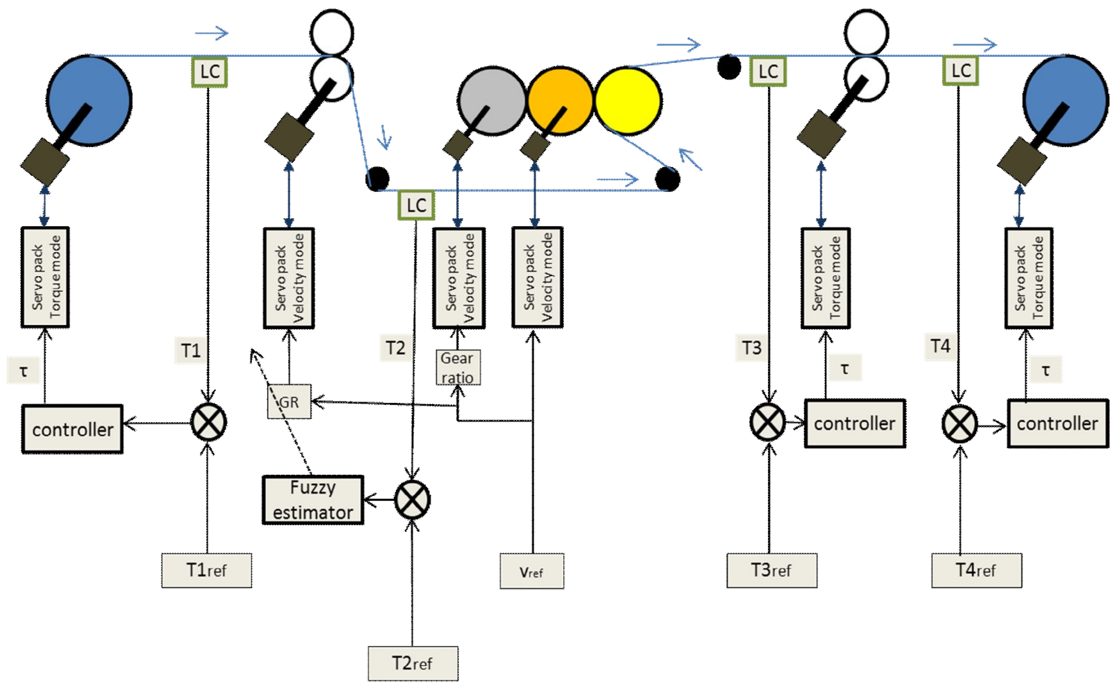


Fig 3.1.5 Overall control system with fuzzy GR estimator.

Further it can be concluded that the rate of change of tension with respect to time is proportional to the difference in linear velocities between offset and the previous in-feed roll. V_k and V_{k-1} are the control variables that can be controller with the aid of servo packs.

$V_k = R_k * \omega_k$ and $V_{k-1} = R_{k-1} * \omega_{k-1}$

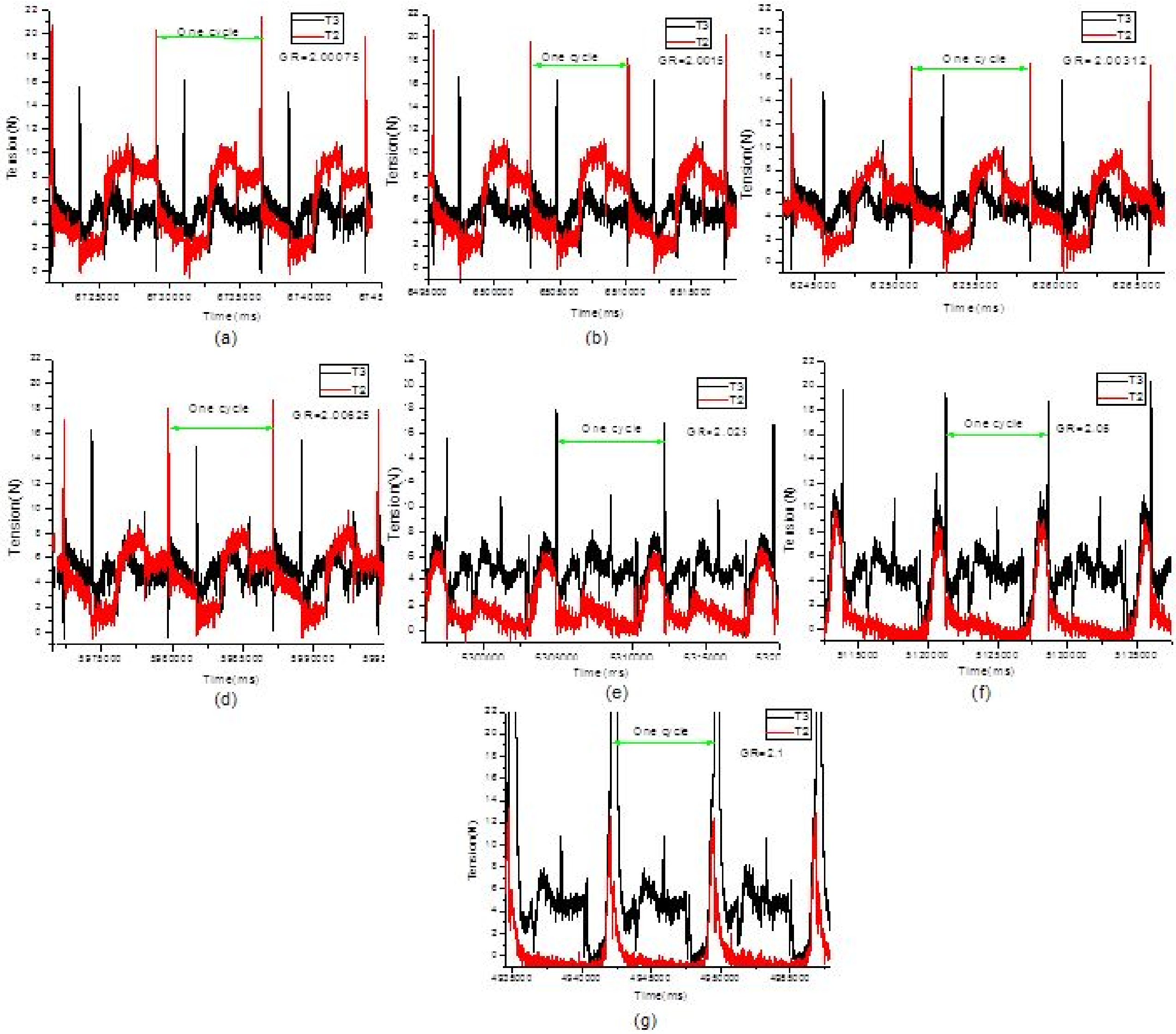
R=radius if the driven roll and ω=angular velocity of the servo motor. Subscripts indicate the span number.

Thus the in-feed drive and offset drive are electronically line shafted to each other. The final control system is as shown in figure 3.1.5. Since the radius ratio between offset and in-feed is 2, the ideal ratio between their velocities is given by GR as

$GR=2$

But this *GR* is not very useful because it was measured while the system was stationary. When the system is in motion the velocity ratio between offset and impression roll is bound to change as the offset rollers engage and disengage with the impression roller almost like a cam with sharp accelerations and decelerations. By changing the value of *GR* based on error in tension it should be possible to control the tension. Fuzzy logic provides excellent and intuitive tools for this type of interpolation. Fuzzy logic estimator as shown in figure 3.1.5 has been used to perform this feedback control.

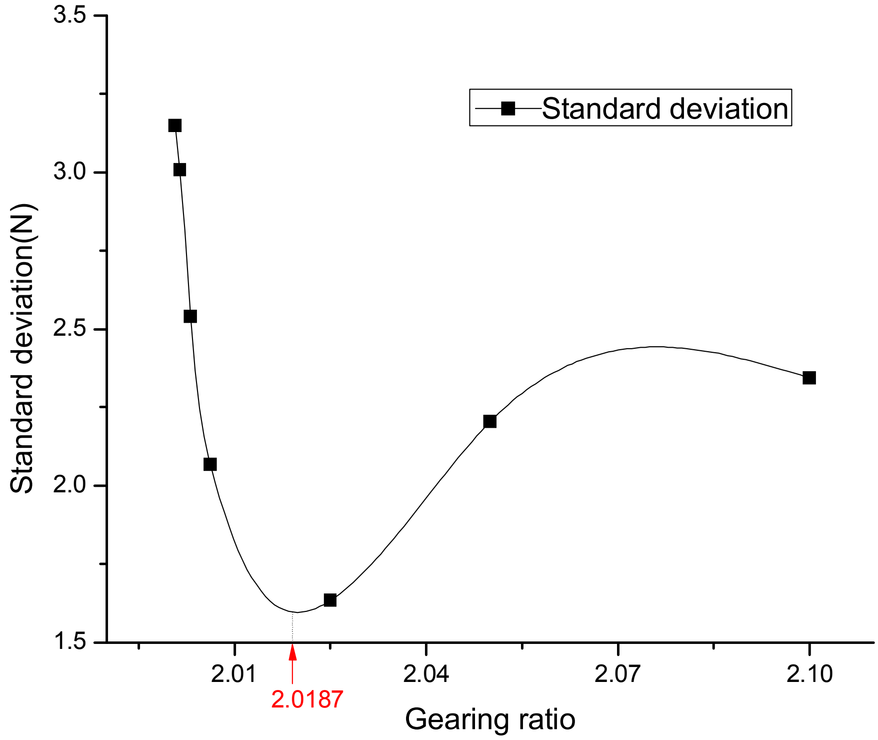
Fuzzy logic based control can be done in two ways. One way is to build a fuzzy model of the system and the other way is to build a controller based on operator experience. In this paper the operator experience is used. Therefore the fuzzy controller is based on experimental data. Experiments were carried out by altering the gearing ratio. The web spans of interest are spans 2 and 3 which have tensions *T2* and *T3*, because they are the spans immediately before and after the offset printer. The reference tension is set at 5N and reference velocity is 0.04m/s. When a constant GR of 2 is used the tension in span 2 never reached the reference tension and also fluctuated considerably. And the result can be seen in fig 3.1.4. Upon increasing GR, the web tension T2 started to oscillate about the reference tension. The experiment was continued until the system began to undershoot and finally overshoot again. The results of experiments with different GR values can be seen in figures 3.1.6(a)-(f). As can be seen it is difficult to interpret much from the visual representation. Hence experimental data from one cycle of operation from each of the seven experiments is chosen and their standard deviation is calculated. Standard deviation is a useful statistical tool that can be used to measure the extent of deviation of tension from its mean. In this case we need the least possible deviation from mean. That is a value of GR that causes minimum deviation of tension from its mean. Standard deviation of tension against GR is shown plotted in figure 3.1.7. A spline is fit into this plot and as can be seen the Standard deviation reaches its minimum at 2.0187. Now we need to interpolate around this value based on web tension error in order to control the tension. It may seem counter intuitive to interpolate based on the minimum standard deviation instead of the mean tension error. But it is the best method because although the mean may be closer to reference tension it is still open loop tension control and as is evident from equation (3.1.1), tension of previous span can effect tension of the given span. The idea behind the proposed controller is to interpolate the value of GR based on the tracking error of T2. Fuzzy logic is primarily an interpolation tool that is suitable for this type of control. The fuzzification and defuzzification sets for the fuzzy estimator are given in fig 3.1.8(a) and



(b). Fi

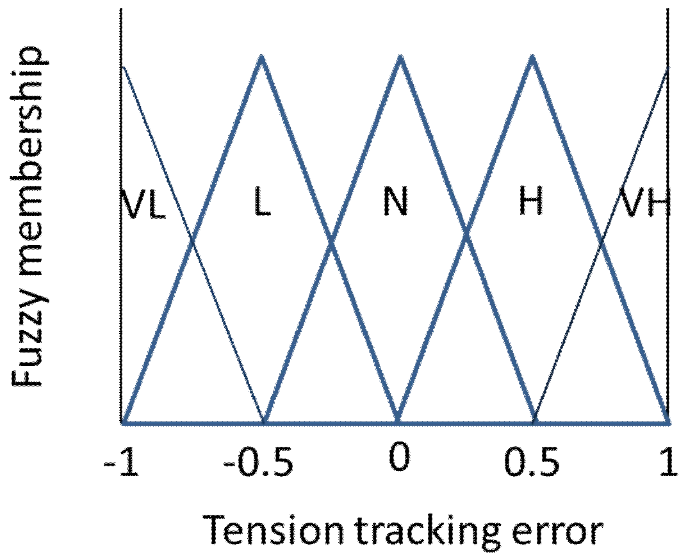
gure3.1.6 System response for different values of GR. The cycles under consideration are indicated;

(a)GR=2.00075;(b)GR=2.0015;(c)GR=2.00315;(d)GR=2.025;(e)GR=2.025; (f)GR=2.05;

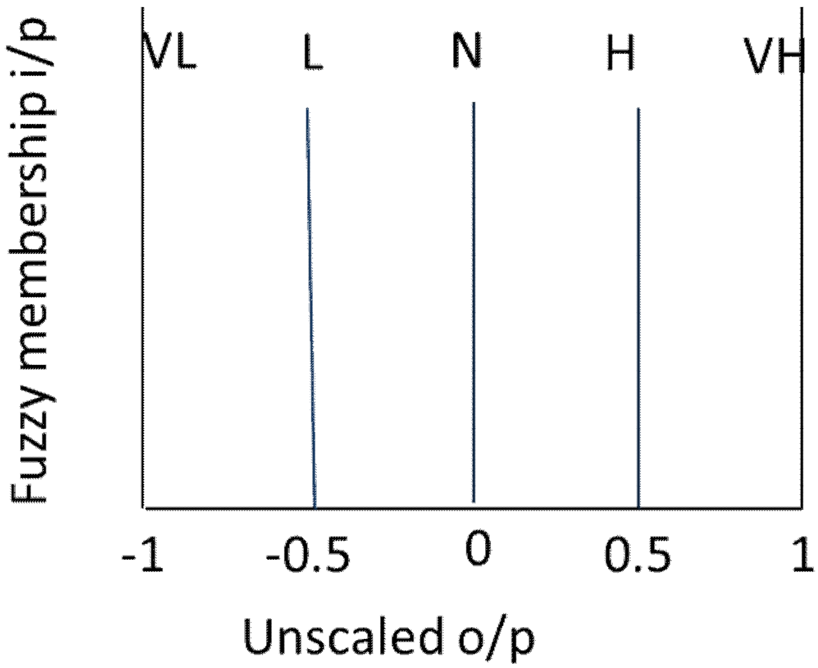


(g)GR=2.1.

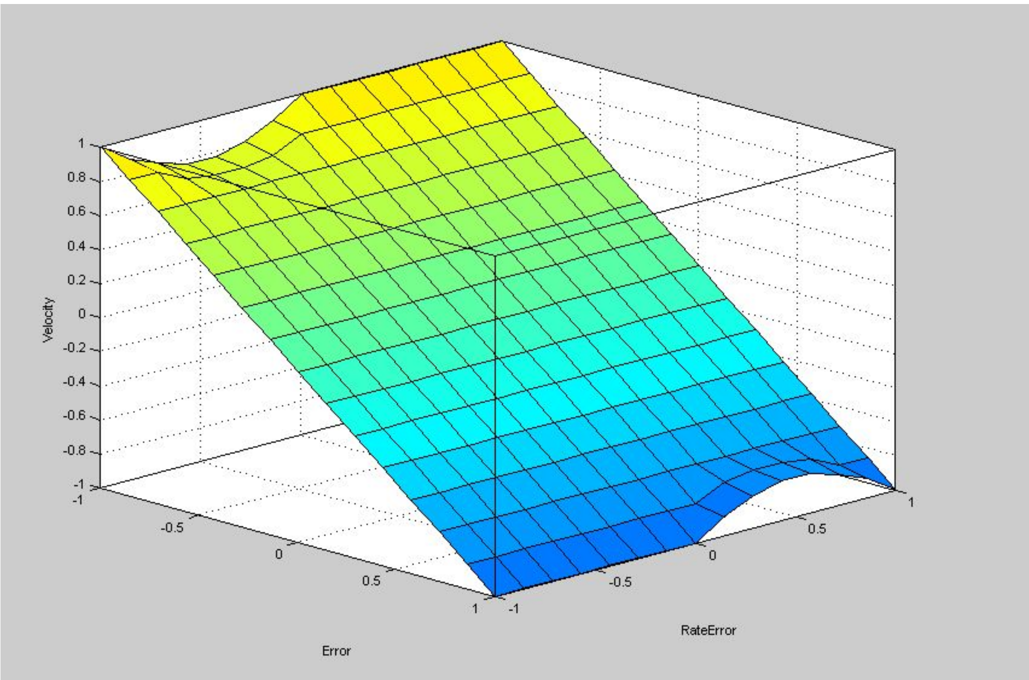
Fig 3.1.7 Standard deviation Vs GR. Minima of standard deviation is marked at GR=2.0187



(a)



(b)



(c)

Fig 3.1.8 (a) fuzzy input set; (b) Fuzzy output set; (c) Fuzzy control surface

The input to the sets in fig 3.1.8(a) is tracking error of the T2 which is given by

e=T2ref-T2 ………………………(3.1.2)

The rule base is as shown in table 3.1.1. The fuzzy sets in the table have the following linguistic meaning, *VH*=very high; *H*=high; *N*=nominal; *L*=low; *VL*=very low. "&" in the rule base is the fuzzy "AND" operation.

Table 3.1.1. Fuzzy rule base

	Antecedent		consequent
If	VL	then	VH
If	L	then	H
If	N	then	N
If	H	then	L
If	VH	then	VL
If	VL & VL_d	then	VH
If	VH & VH_d	then	VL
If	VL & L_d	then	H
If	VL_d & L	then	H
If	VH & H_d	then	L
If	VH & H	then	L

In the rule base the subscript "d" indicates that the error rate is used as input. The rule base is based on experimentation with different combinations. The fuzzy surface is given in figure 3.1.8(c). Here X and Y axis represent error and rate error while Z axis represents the fuzzy output. Details of fuzzy estimator are shown in figure 3.1.9. In it the FIM is the fuzzy inference mechanism. The well-known centroid method is used in FIM along with the rule base to obtain the defuzzified output as given in equation (3.1.3). For convenience of computation the domain of input (i/p) of FIM is (-1,1) and output (o/p) from the FIM are in the range, (-1, 1). For this purpose the i/p and o/p have to be scaled within (-1,1).

$\boldsymbol{\tau}=VL(e)*1+L(e)*0.5+N(e)*0+H(e)*(-0.5)+VH(e)*(-1)+VL\wedge VL_d(e)*1+VH\wedge VH_d(e)*(-1)+$

$VL\wedge L_d(e)*0.5+VL_d\wedge L(e)*0.5+VH\wedge H_d(e)*(-0.5)+VH_d\wedge H(e)*(-0.5)$

………………………(3.1.3)

In the above equation, the symbol "∧"denotes the fuzzy "AND" operation. The expression $VL\wedge VL_d(e)$, is mathematically interpreted as follows:

$VL\wedge VL_d(e)= VL(e) \wedge VL(d(e)/dt)$

$= \min.(VL(e) ,VL(d(e)/dt))$

..……………………..(3.1.4)

VL(e), is the fuzzy membership value of e in the membership functionVL().

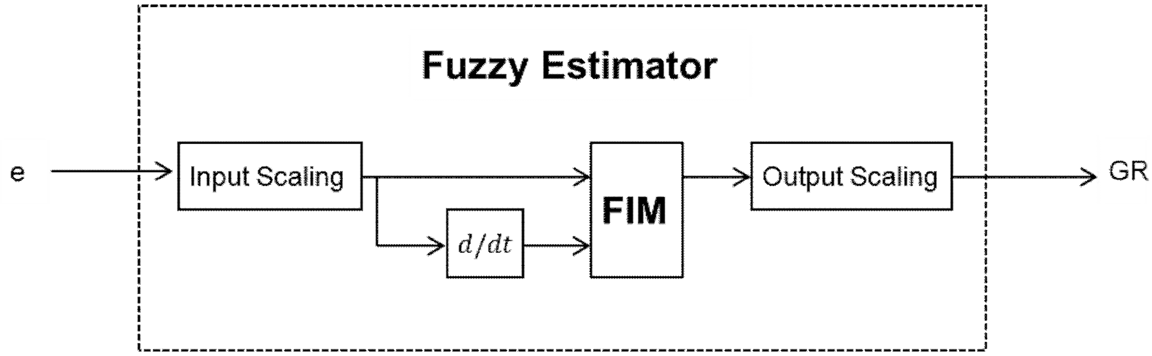


Fig 3.1.9.Fuzzy estimator-block diagram

There are three ways to tune a fuzzy logic system: change rule base, change i/p scaling or o/p scaling. This fuzzy estimator has to scale about 2.0187, which means that "0" output from FIM must correspond with 2.0187 of the fuzzy estimator output. Now the input scaling is calculated manually.

Input scaling function in figure 3.1.9, is given by

$F(e)=0.45*e$

And the output scaling function uses $\boldsymbol{\tau}$ from equation (3.1.3) and computes *GR* given by

$GR=G(\boldsymbol{\tau})=2.0187+\boldsymbol{\tau}$

The results of a well-tuned system are shown in figure 3.1.10. Mesh patterns were printed using the proposed system and the microscope image of printed product is shown in figure 3.1.11. The mesh pattern has a width of 17.9 microns and the pattern did not have discontinuities.

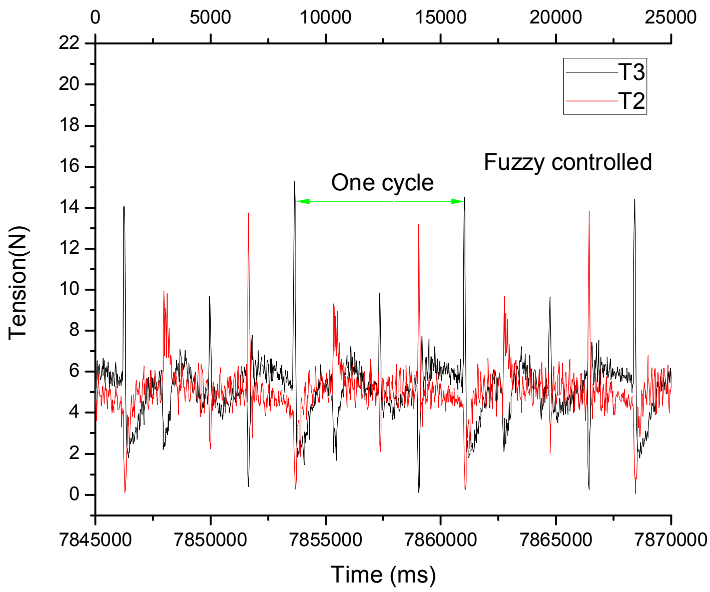
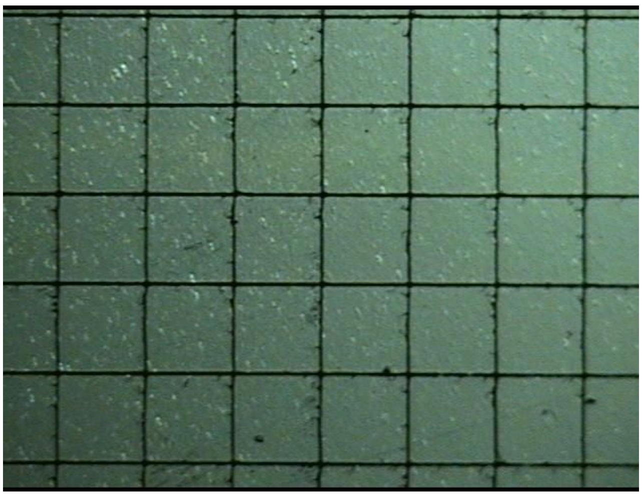


Fig 3.1.10 Results when using fuzzy GR estimator



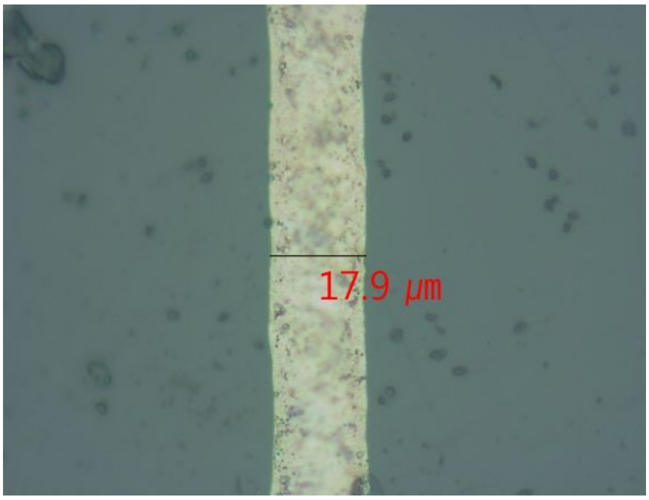


Fig 3.1.11 Finished mesh pattern(top) and single magnified silver pattern with scale(bottom)

3.2. Reduction of interaction between spans using fuzzy logic

Control of web tension is crucial for maintaining quality of products processed on roll-to-roll (R2R) system. But converting industries tend to neglect these interactions and use decentralized single-input-single-output (SISO) control approaches to deal with tension control. Multi-input-multi-output (MIMO) approaches have been reported in literatures but are practically not in use. Interaction between the various tension spans is unavoidable as they are all connected by a single web. Disturbances produced in a span tend to travel further downstream along the direction of web travel. When the number of spans is less or the disturbance amplitudes are small this does not present a big challenge and simple SISO control is sufficient. But when the amplitudes of disturbances produced in processing is large -as is the case with printed electronics- or the number of spans is large or both, then the interactions cannot be neglected. R2R based offset printers have the potential for mass production of precision printed electronics. In this section a fuzzy logic based hybrid approach has been followed that specifically targets the printed electronics industry and this method considerably reduces the interactions. The algorithm has been designed such that it takes information from previous span to reduce the propagation of tension disturbances to the given span. This has been achieved through online computation of correlation coefficient and reducing the interaction through feedback control.

3.2.1. Introduction

The web handling system also known as the roll-to-roll system is a mass production and processing tool used to process material in the form of web-film, paper, fabric etc. Figure 3.2.1(a) shows the R2R system used during experiments for this paper. It is made up of six spindles driven by servo motors which are housed on the machine frame. The motors transport web-which in this case is made of poly ethylene terephthalate (PET)-from a roll of web and processes it-offset printing- and then rewinds it. During this travel from the un-wind to the re-wind section the web has to be maintained at a precise tension. There are numerous idle rollers to guide the web through the machine. Also there are load cells that give feedback of web tension. The whole system is controller via a PXI system. The overall schematic representation of the machine configuration is shown in figure 3.2.1(b). Figure 3.2.1(c) shows the block diagram of conventional control architecture. The load cell (LC) measures the tension in a given span. T1 through T4 are tensions of the four spans. This data is collected in a PXI where it is processed and torque output is sent out to the servo packs. Offset printing is a promising technology for printed electronics. When it is used along with R2R system the printed electronics can be mass produced. Offset printing system used in printed electronics is distinct from that used for printed media. It introduces disturbances into the R2R system. These disturbances tend to travel further downstream. In the pilot R2R system shown in figure 3.2.1(a) only one printing system exists but in a full electronics printing system there would be a series of offset printing units to print consecutive layers and these disturbances will tend to grown with every printing step. Conventional control architecture as shown in figure 3.2.1(c) is ill equipped to deal with this sort of problem. Hence a new hybrid fuzzy control system has been implemented that in a sense decouples the control of the tension spans.

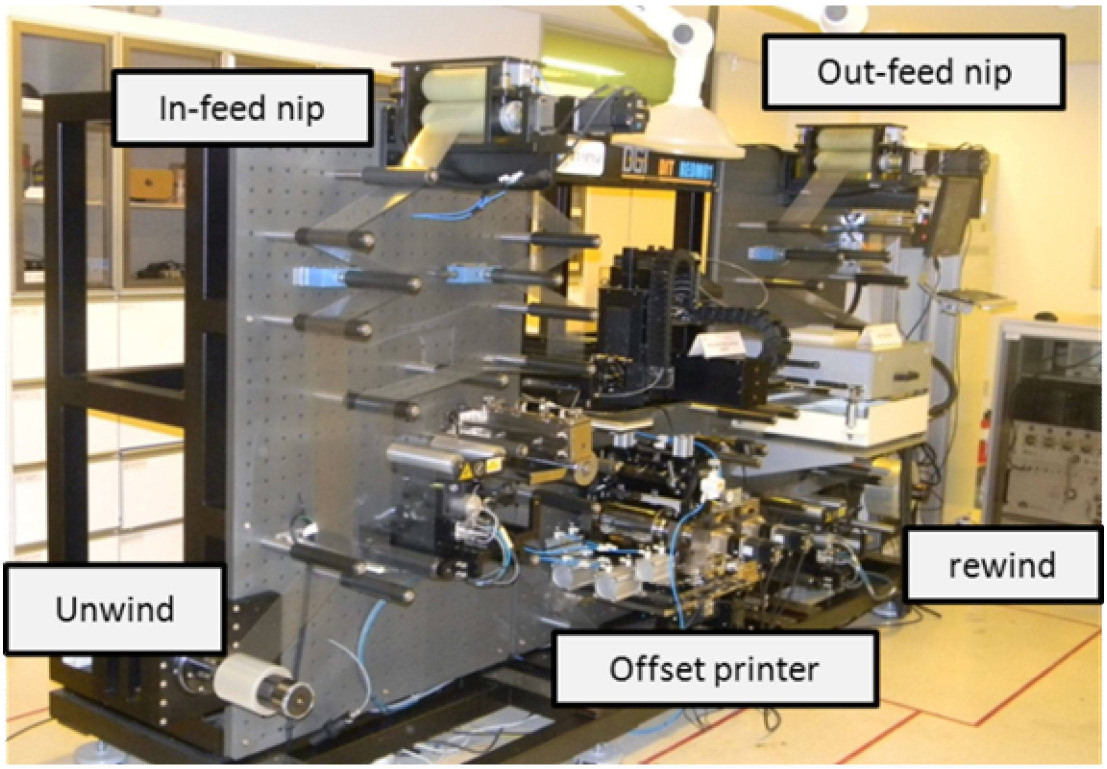


Fig 3.2.1(a) R2R system

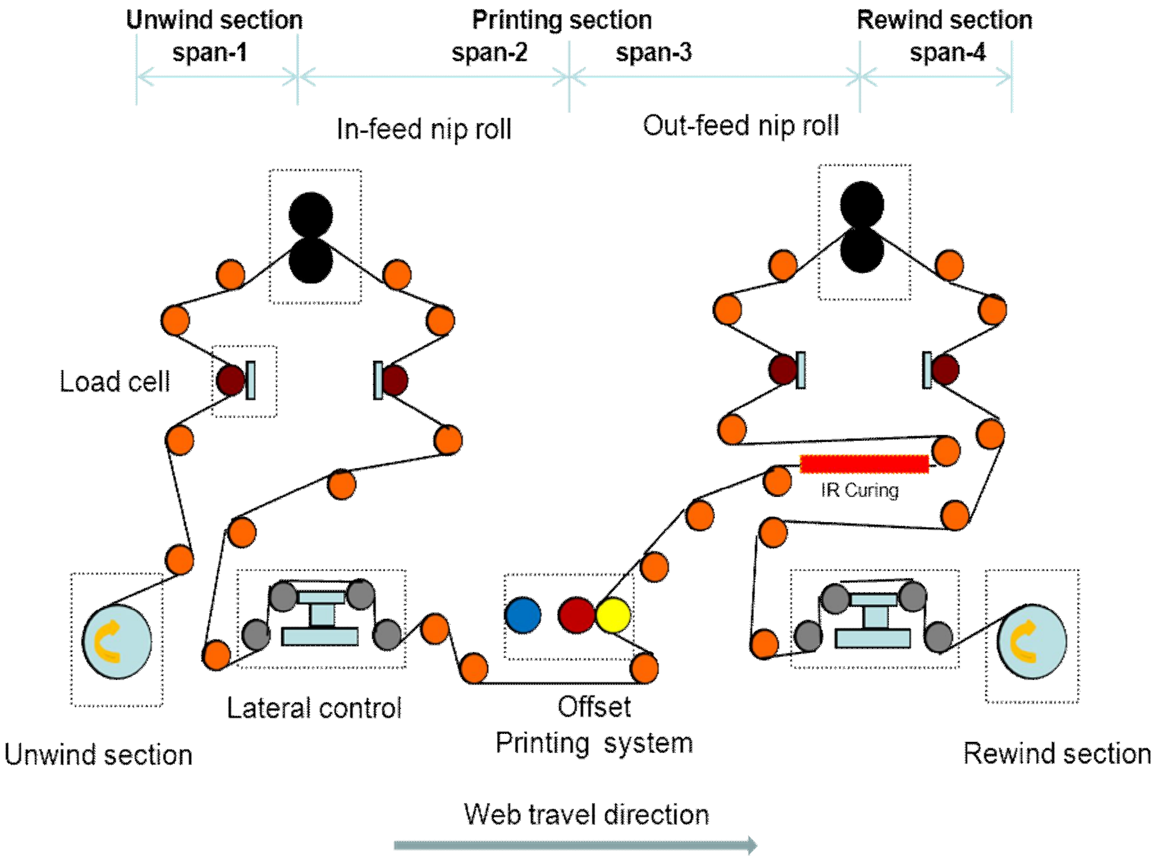


Fig 3.2.1(b) Schematic representation of R2R system

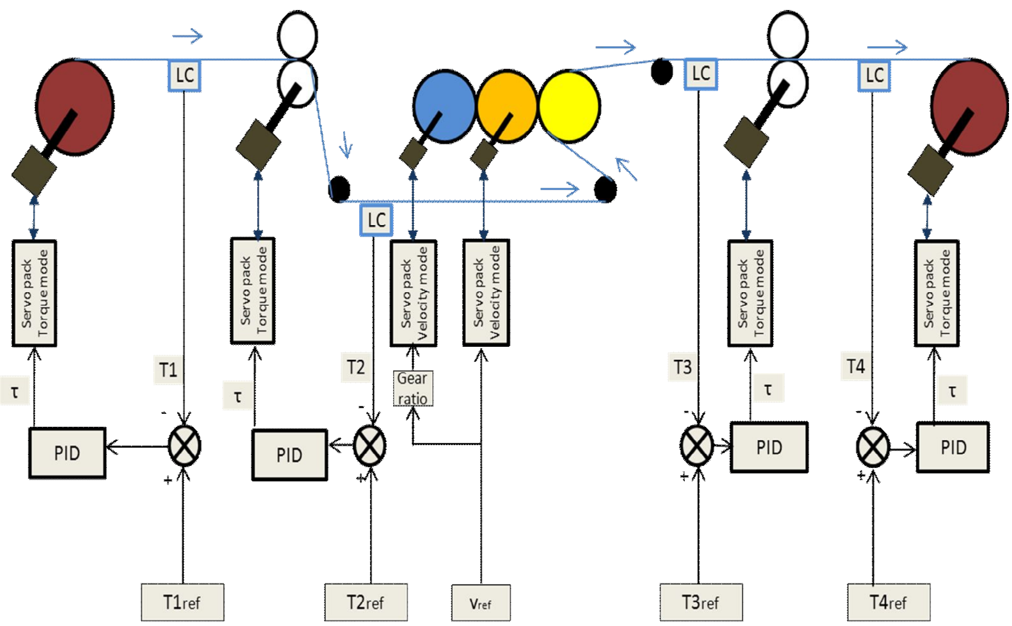


Fig 3.2.1(c) Conventional control architecture

Although in theory the control of a 4-span R2R system like this system is to be dealt with as a multi-input-multi-output (MIMO) system, but this is hardly practical. Accurate modeling is required to achieve good performance for each configuration of the machine and this also reduces flexibility of the system to operate with different raw materials. Hence the industries neglect the interconnected nature of the system and break the control problem into single-input-single-output (SISO) systems which is usually PID controller. This approach is suited if the disturbances in tension are less or when the processing of web is not effected by tension fluctuations. Printed electronics requires very precise tension control and the process of offset printing itself generates disturbances. For this technology to be scalable to the industry the solution needs to be free of system modeling and easily tunable. Keeping these in view a new fuzzy hybrid tension control system has been developed that mimics a PID controller but also takes feedback from the upstream span as shown in figure 3.2.2. The resulting controller is capable of almost eliminating the propagation of disturbances. Besides being of use to printed electronics industry the aforementioned technique will also benefit countless converting industries that employ R2R system with very large number of tension spans.

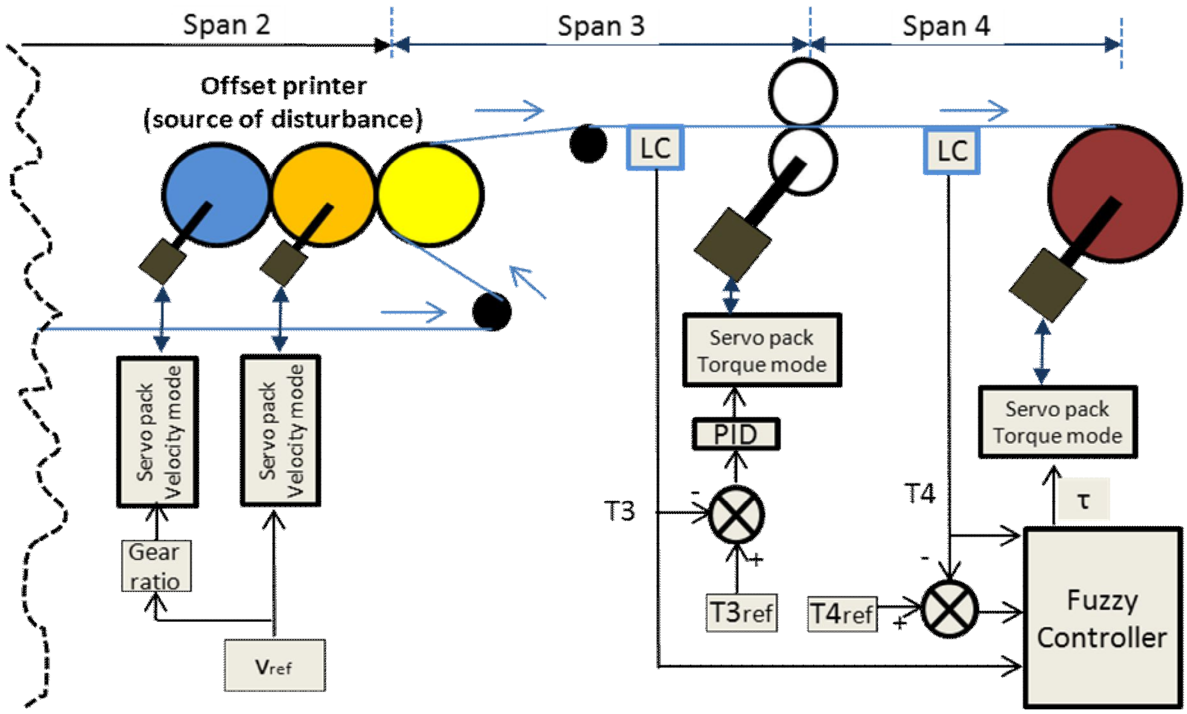
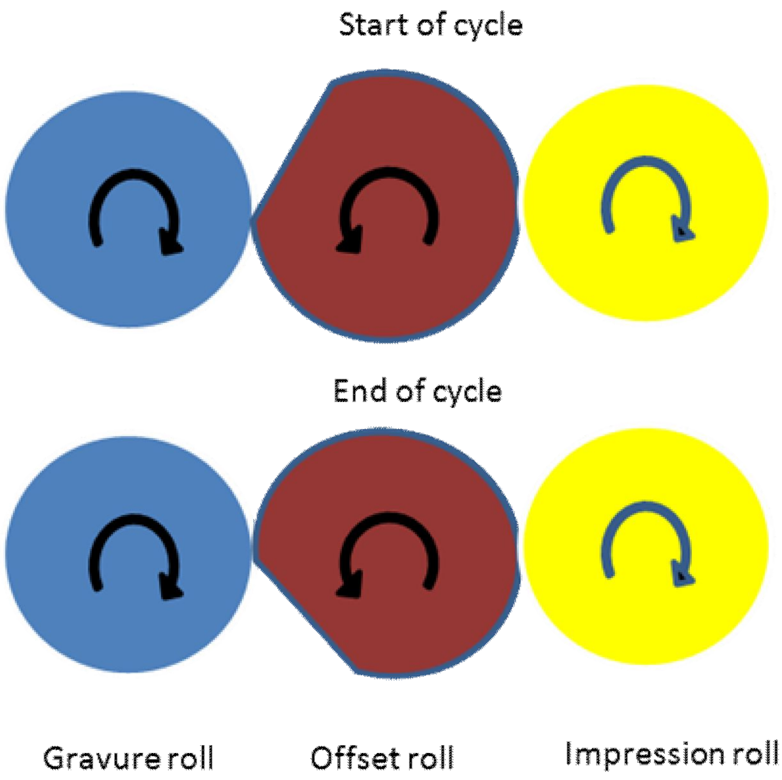
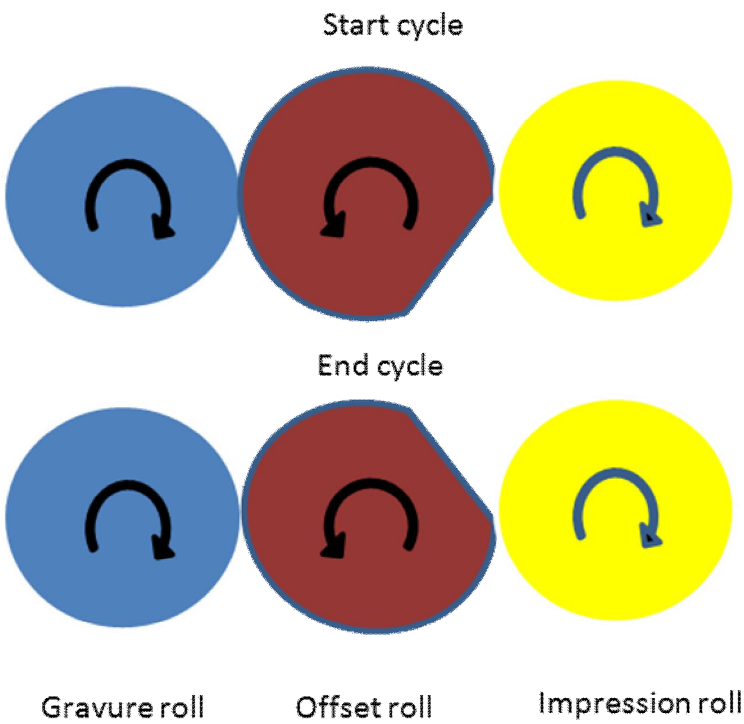


Fig 3.2.2 Proposed hybrid controller


Start of cycle
End of cycle
Gravure roll
Offset roll
Impression roll

(a)


Start cycle
End cycle
Gravure roll
Offset roll
Impression roll

(b)

Figure 3.2.3 (a) Offset-gravure non-contact phase; (b) Offset-impression non-contact phase

3.2.2. Methods and materials

As can be seen in figure 3.2.1(c) there are a total six prime movers in the web machine. These servo packs are of Mitsubishi brand; servo-amp (MRJ2S70A) and servo motor (HC-KFS-73). The interface hardware is from National Instruments. LabVIEW 8.6 software was used to write the controller code. The web material is PET. It had a thickness of 0.1mm and width of 120mm.

3.2.3. Causes and consequences of disturbances

There are several causes for production of tension disturbances. The nature of the printer is such that the offset roll comes in contact and loses contact with both the gravure and impression rolls for every cycle of operation. These phases are shown in figure 3.2.3.The details of the disturbances is given in section 3.2. Furthermore the offset roll surface (PDMS blanket), has an affinity with the web (PET). This leads to a plucking of the web when the contact phase between the offset and impression roll comes to an end. These disturbances are reasonably periodic with respect to the rotation of the offset roll as shown in figure 3.2.4. Although this paper specifically addresses the problem of propagation of the aforementioned tension disturbances from span 3 to span 4, the algorithm is generic and is not dependent on the type of disturbance. One of the problems of allowing the propagation of these disturbances is that when operating the R2R system at low tensions (5N) is that the web guide(lateral controller) shown in figure 3.2.1(b), becomes ineffective causing serious lateral error in the web that is wound.

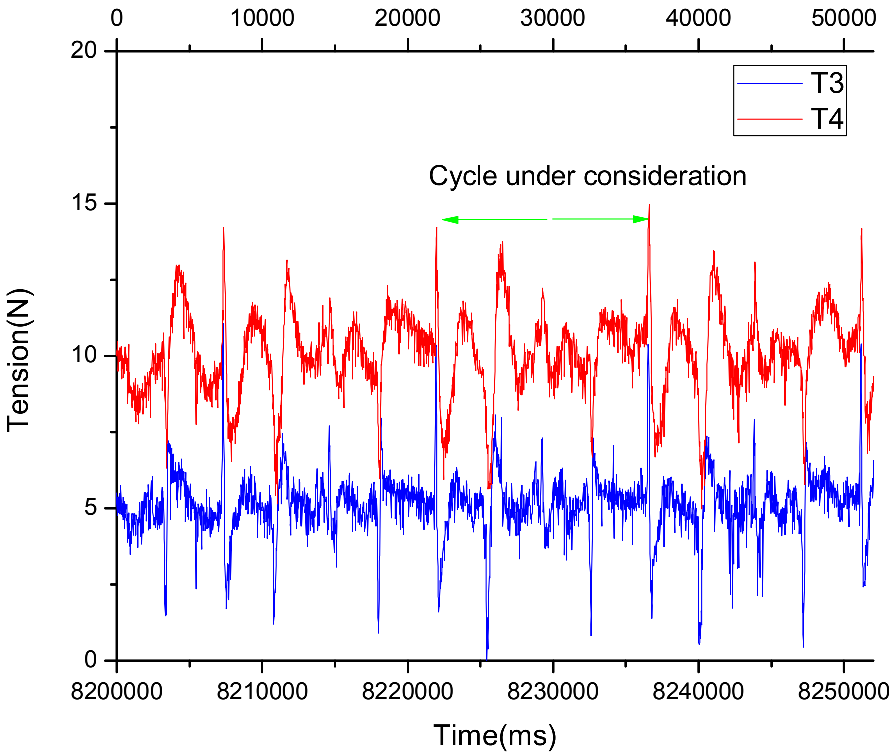


Figure 3.2.4 Tension in spans T3 and T4 plotted against time.

3.2.4. Control system design

3.2.4.1. Open loop control design

The dynamic equation (same as equation 2.1) for tension in a given span is as follows

$$dT_k(t)/dt=(-V_k*T_k(t)+V_{k-1}*T_{k-1}(t))/L+C[V_k-V_{k-1}] \quad \text{……………………………..……………(3.2.1)}$$

Where, T in T_k is the tension of a span and subscript K denotes the span number counted from un-winder; V_k is the velocity of K_{th} web span which is measured as the linear velocity of the downstream driven roller of the K_{th} span; L is the span length, and C is the spring constant of web.

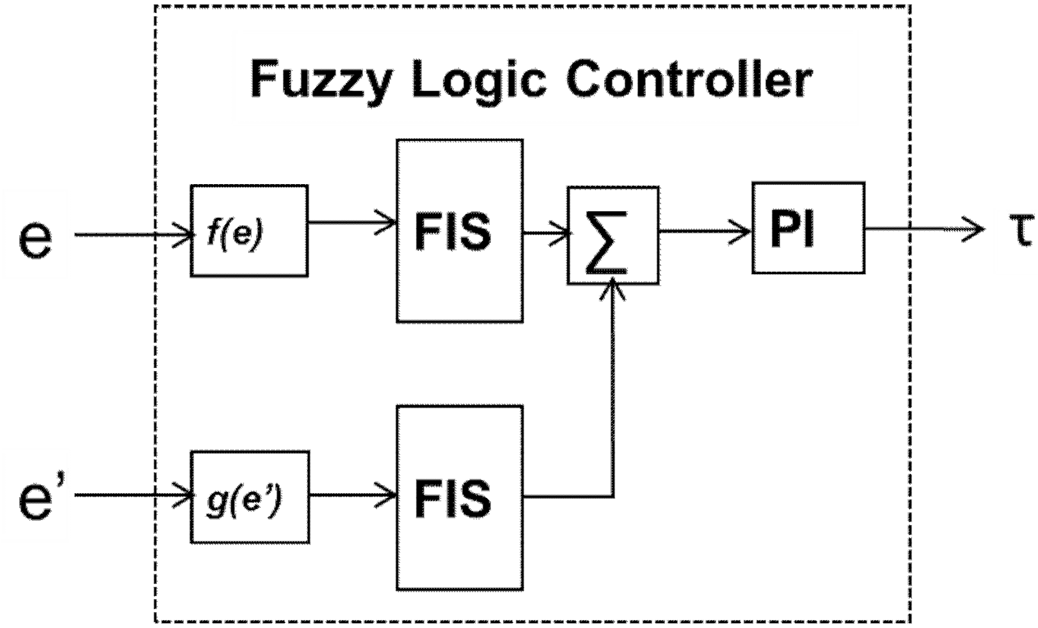


Figure3.2.5 Block diagram of fuzzy controller

From the above equation the following can be inferred:

1. The rate of change of tension in the given span is proportional to the difference of velocity between the previous and the current spans.
2. There is a strong correlation between the tension in the previous span and the current span.

The new control system is required only for span 4, as the disturbances are introduced at span 3 by the offset printer. In order to design the control system the existing PID control system shown in figure 3.2.1(b) is first replaced by a fuzzy system that is similar to it. The fuzzy system is same as the discrete time PI controller in all respect except that the error undergoes fuzzification and defuzification. The proposed controller is shown in figure 3.2.5. The terms in figure 3.2.5 can be explained as follows:

e= error in tension of current span=*T4ref-T4*

e'= error in tension of previous span=*T3ref-T3*

f(e)=input scaling function of error in tension of current span= *e/T4ref*

g(e')=input scaling function of error in tension of previous span= *e'/μ*

It is obvious that if the input scaling factor μ is sufficiently large then *g(e')* will be very small. In this case a value of 100 is enough to make *g(e')* tend to zero. Now with $g(e') \rightarrow 0$ it can be said that the fuzzy logic controller in figure 4.2.5 is actually a PI controller with fuzzified error. *FIS* is defined as fuzzy inference system. Essentially it takes error as input and using the fuzzy sets in figure 6 and the rule base that will be derived shortly, the error is fuzzified such that we get a performance from feedback control that is similar to a PI controller.

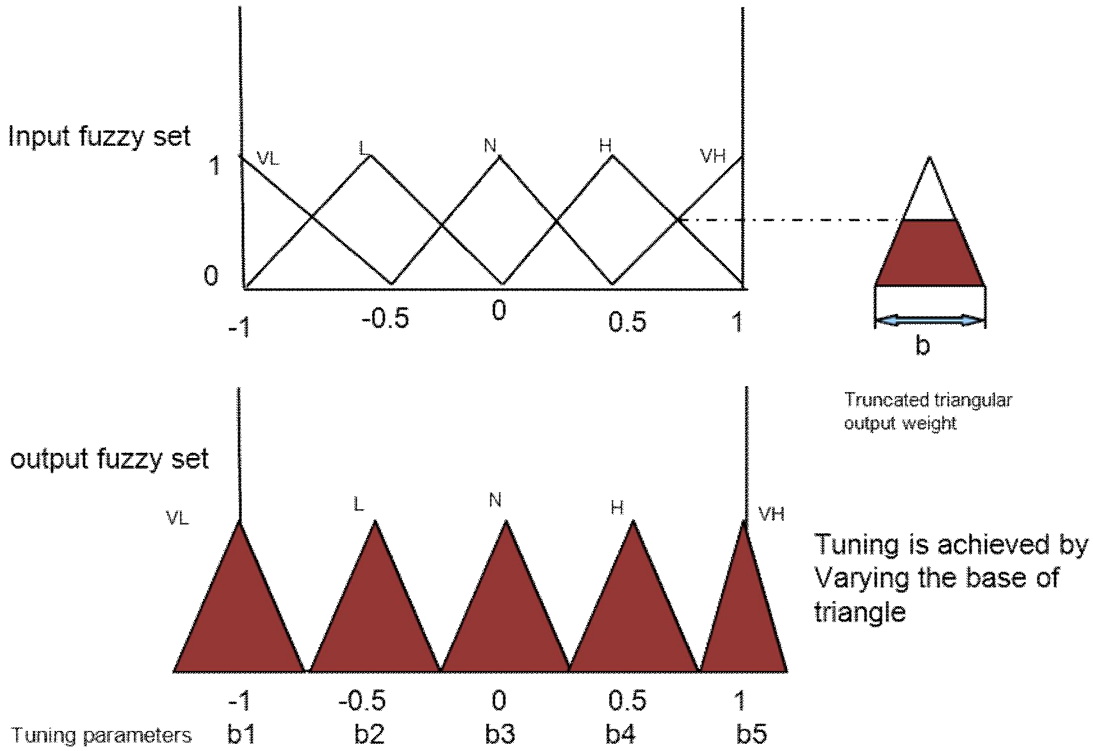


Figure3.2.6 Fuzzy sets

When all the external disturbances are disregarded it is possible to establish a clear linguistic relation between the input error and output error as given in the rule base. The base length of the truncated triangles *b1, b2, b3, b4* and *b5* shown in output sets in figure 4.2.6 are used as tuning parameters. Again the tuning is done to get a performance similar to the PI controller, in terms of overshoot, settling time etc. It is assumed that a large positive error in tension *e* requires a large negative torque and large positive *e* requires a large negative torque. Similarly a diminished positive error requires a diminished negative torque. Based on this linguistic premise the fuzzy rule base is formulated. The input space and the output space are partitioned into five fuzzy sets. Fuzzy rule base for the inference mechanism shown in figure 5 is given as follows:

if e is V L then e_f *is VH*

if e is L then e_f *is H*

if e is N *then* e_f *is N*

if e is H *then* e_f *is L*

if e is VH *then* e_f *is VL*

In the above rule base "*VL*" stands for "very less", "*L*" stands for "less", "*N*" stands for "nominal", "*H*" stands for "high" and "*VH*" stands for "very high". And "*e*" and "e_f" stand for scaled tension error and scaled torque output respectively.

The output of the inference mechanism is given by the following equation:

$e_f = M(VL\ e)\ \ Ar(b5, M(VL\ e))\ (1) + M\ (L\ e)\ Ar(b4, M\ (L\ e))\ \ (0.5) + M(N\ e)\ (0) + M(H\ e)\ Ar(b2, M(H\ e))$ $(-0.5) + M(VH\ e)\ Ar(b1, M(VH\ e))\ (-1)$ ……………………………………(3.2.2)

Where,
M(*VL e*) is evaluated as the membership value of e in the fuzzy set *VL*.
Ar(.) is the area of the truncated triangular output fuzzy sets evaluated as
$Ar(M(VL\ e))=(2*\ M(VL\ e) - M(VL\ e)^{2})*b/2$
Equation (2) can be described as follows:

1) The inference mechanism shown is similar to the centroid method, with the difference being caused by the weights.
2) Overall input space as shown in figure 3.2.4can be divided into 6 regions, with 2 regions at the both extremes being covered by one fuzzy set each and the remaining 4 regions have two fuzzy sets each.
3) Output from the inference system is determined by the ratio between the area of the truncated triangles at the output set. The transition from one region to another can be made smooth or abrupt depending on the difference in the base length of the weight triangles corresponding to the region.

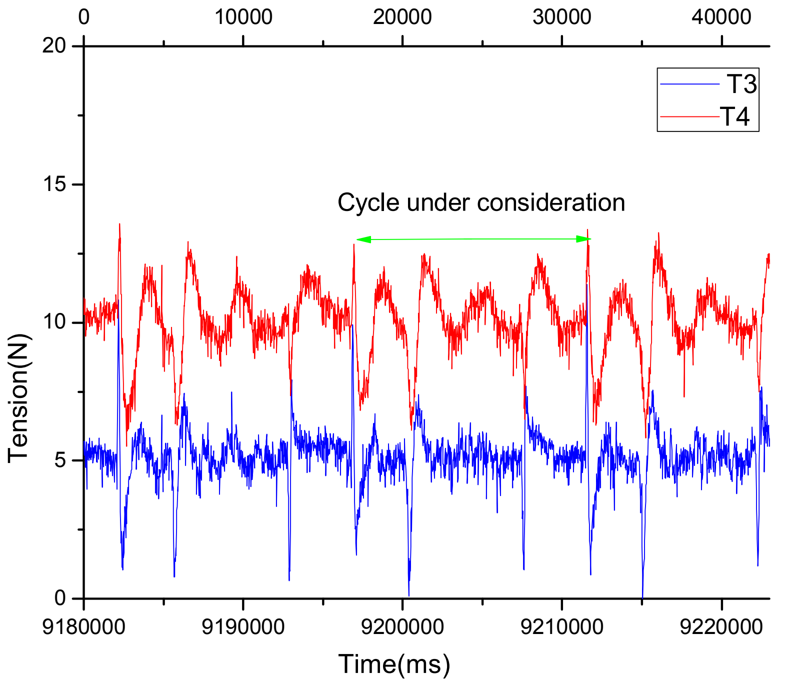
It is evident from figure 4.2.5 that there are two *FIS* in the control system. The one with *g(e')* as input has practically negligible output because of large value of μ.This output is given by

$e_f' = M(VL\ e')\ \ Ar(b5, M(VL\ e'))\ \ (1) + M\ (L\ e')\ Ar(b4, M\ (L\ e'))\ \ (0.5) + M(N\ e')\ (0) +$ $M(H\ e')\ Ar(b2, M(H\ e'))\ (-0.5) + M(VH\ e')\ Ar(b1, M(VH\ e'))\ (-1)$……………….(3.2.3)

The total value of fuzzified error going into the PI controller in the fuzzy controller is

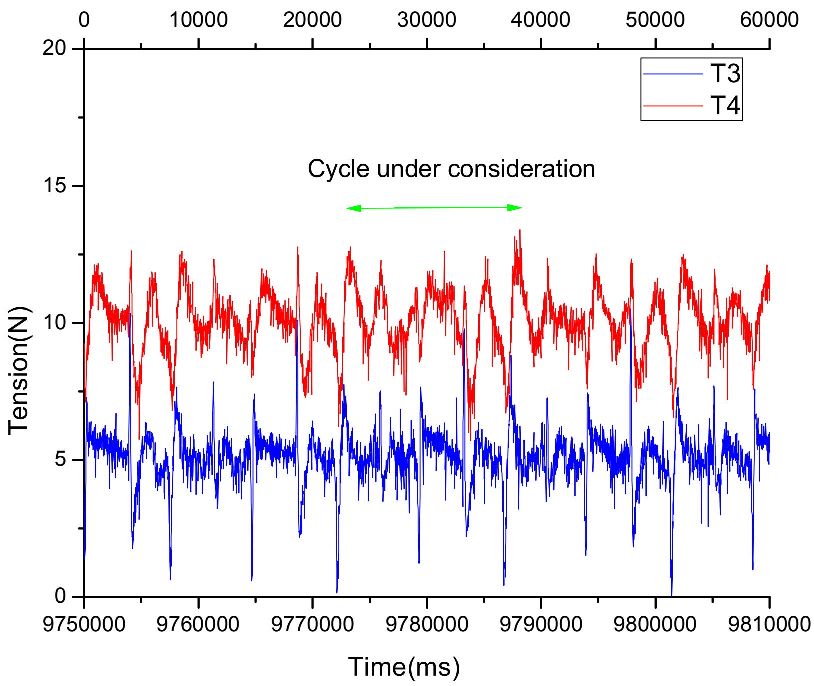
$e_{total}=e_f+e_f'$ ………………….....(3.2.4)

Now the μ value is gradually decreased to make the value of e_f' more effective in the overall control output of the fuzzy controller. Major changes were observed in the domain of μ in (5, 25). Therefore only the experimental data from this domain has been considered. It can be seen from figure 3.2.7(a)-(e) that as the value of μ increases, the correlation between T3 and T4 diminishes. The correlation coefficient is an effective tool to measure the degree of correlation between two quantities. The Pearson's correlation coefficient is one of the most basic of the correlation coefficients. It gives an output in the range (-1, 1). It is a measure of the extent of linear relation between two quantities; a value of zero implies that the two quantities vary independently; a positive large value implies that a strong relation exists and as one value increases the other increases as well; a large negative correlation is a sign that there is a strong relation between the two quantities but as one increases the other tends to decrease. The value of Pearson's correlation coefficient between T3 and T4 of the data points marked in the figure 3.2.7(a)-(e). Each of these regions is treated as a sample representing the whole data. The regions marked are in fact one cycle in the operation of the offset printer. A total of 15000 data points make up each region. Correlation coefficient is plotted against the scaling factor μ in figure 3.2.8. It is evident that the correlation coefficient shows a clear trend and it becomes zero as μ approaches 8. The effect of this can also be seen in figure 7(d), in which the μ value is 8, and the disturbances propagated to span 4 is considerably reduced. Now the reference tension T4ref is fixed at 5N and the results can be seen in figure 3.2.7(f).



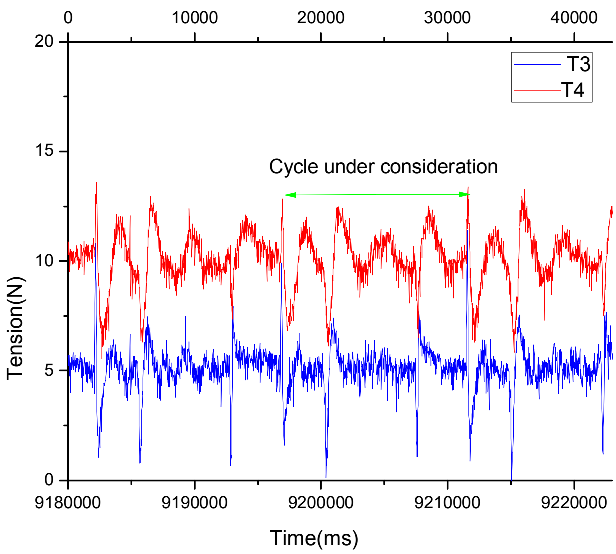
Cycle under consideration
T3
T4
Tension(N)
Time(ms)

(a)

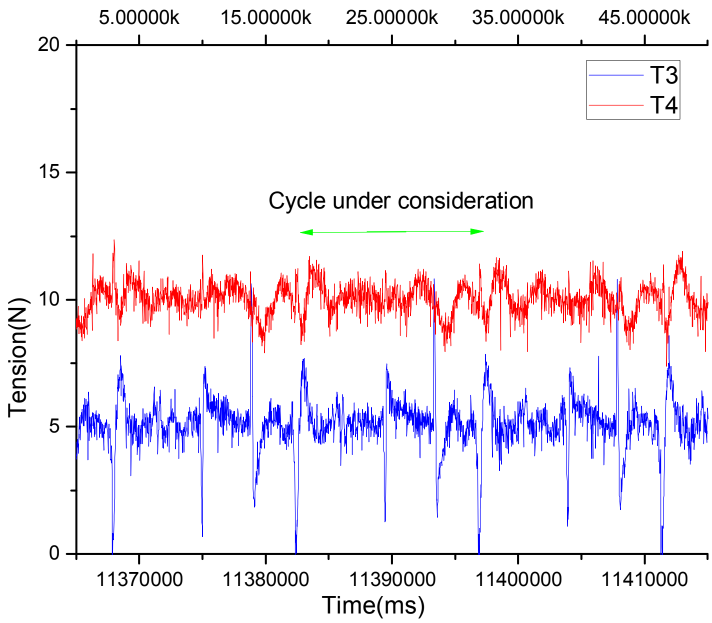


Cycle under consideration
T3
T4
Tension(N)
Time(ms)

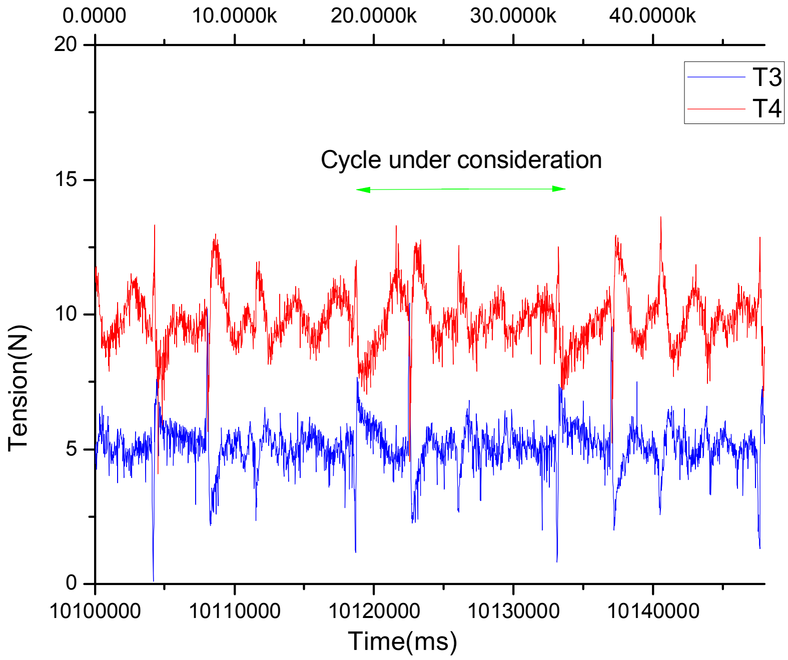
(b)


0
10000
20000
30000
40000
T3
T4
Cycle under consideration
Tension(N)
20
15
10
5
0
9180000
9190000
9200000
9210000
9220000
Time(ms)

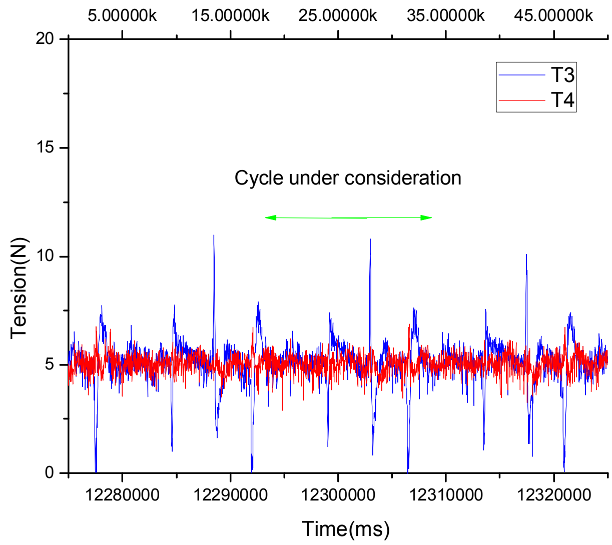
(c)


5.00000k
15.00000k
25.00000k
35.00000k
45.00000k
T3
T4
Cycle under consideration
Tension(N)
20
15
10
5
0
11370000
11380000
11390000
11400000
11410000
Time(ms)

(d)



(e)



(f)

Figure3.2.7 Tension in spans 3 and 4 under different μ ;(a) μ=25,T3=5N, T4=10N;(b) μ=17.5,T3=5N, T4=10N;(c) μ=10 ,T3=5N, T4=10N; (d) μ=8,T3=5N, T4=10N;(e) μ=5,T3=5N, T4=10N;(f) μ=8,T3=5N,T4=5N.

3.2.4.2. Closed loop control design

In previous section the tension disturbance propagation was brought under control by setting a constant value of μ. But the ideal value of μ may not be a constant as has been done and it is bound to change. Therefore instead of using our input μ *can be* calculated online and updated regularly. To achieve this self-tuning nature it is crucial to compute the value of Pearson's correlation coefficient online and update μ regularly based on it. Generally computation of correlation coefficient is a very tedious process for a data set as large 15000 data points but LabVIEW offers this feature as a sub-VI (subroutine). The Pearson's correlation coefficient is in the range (-1, 1) and from figure 4.2.8, a qualitative relation is found that can be stated as follows

An increase of μ will lead to an increase of correlation while a decrease will lead to a decrease in correlation

This is a very simple relation which implies that the μ update can be done using a PI like controller using correlation coefficient as the input. μ is updated as follows.

$\mu=\eta+PI(Corr(T3,T4))$……………………………………………………………..(3.2.5)

where,

η= *seed tuning factor=8*

Seed tuning factor is used so that the self-tuner converges sooner. Since μ value of 8 has already been found to be effective in reducing disturbance propagation it is set as the seed tuning factor.

PI(.)=is a PI controller

Corr(T3, T4)= Pearson's correlation coefficient of the last 15000 data points of T3 and T4.

After fine tuning the system the result can be seen in figure 3.2.9. Tuning factors for PI controller in equation (3.2.5) were found to be K_p=0.1, and K_i=-0.0028.

All the above experiments were performed at a web velocity of 0.4m/s.

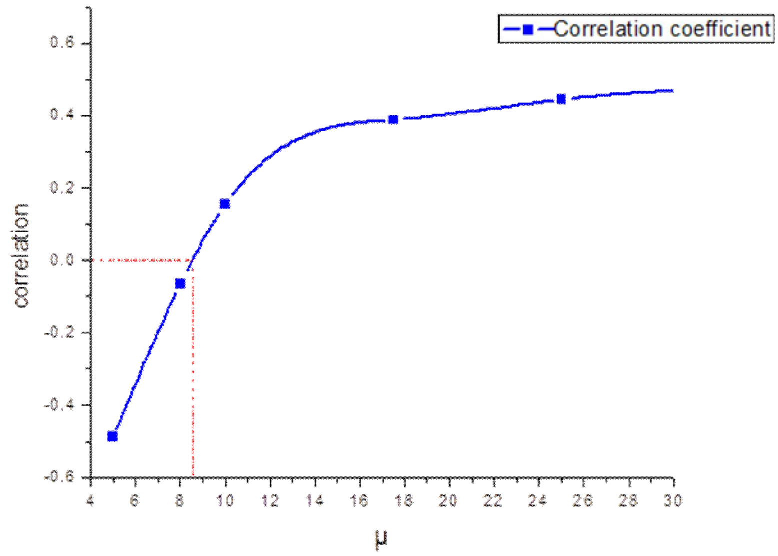


Figure 3.2.8. Correlation coefficient vs scaling factor

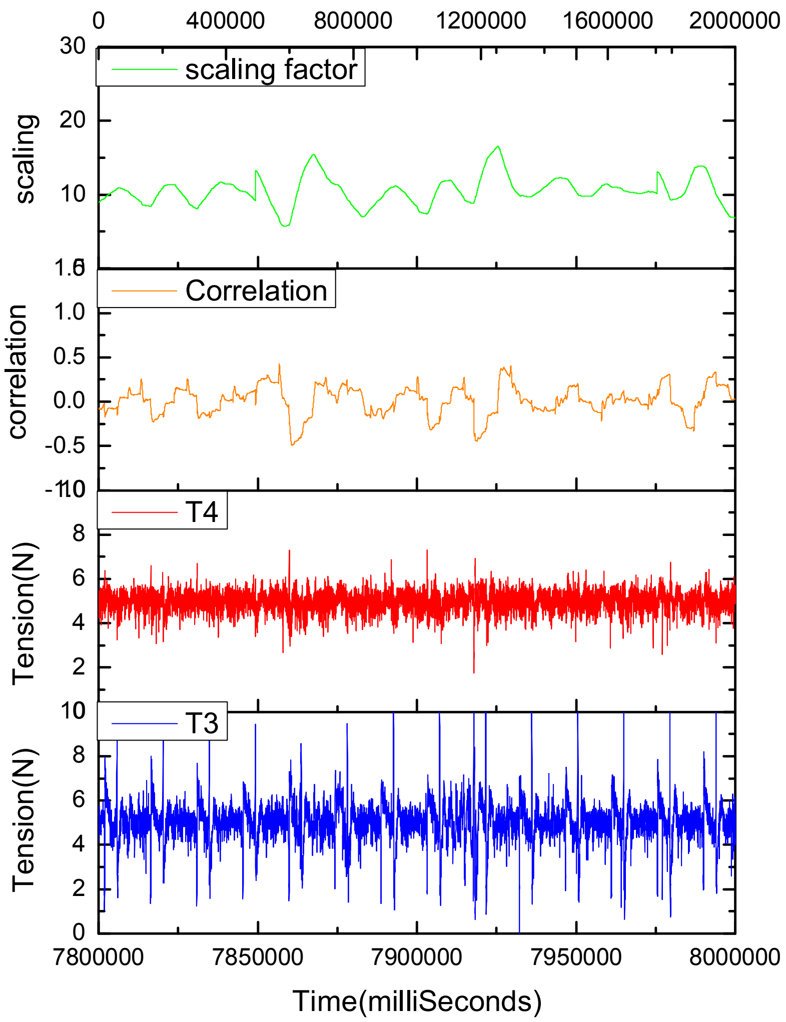


Figure 3.2.9 Final results of the self-tuning controller

3.3. Active dancer based closed loop tension control

Active dancers are used to control web tension in roll-to-roll (R2R) based printing systems. In this section the control system for a compact active dancer system has been designed using fuzzy logic. The dancer system has a proportional pressure regulator as actuator and a potentiometer to measure the displacement of the system. Controller is designed without using a system model. In this case the problem is broken down into two. First the problem is interpreted as a position control problem. A fuzzy logic based controller is designed to achieve accurate position control. Finally tension feedback is introduced using a simple proportional control.

3.3.1. Introduction

Roll-to-roll (R2R), also known as web handling system is a popular tool to process material in the form of thin strips. It finds application in the fields of textile, paper, film, printing industry etc. The R2R system utilized in this paper is shown in figure 4.3.1(a). Schematic representation of the system is shown in figure 4.3.1(b). Its role is to first unwind the material in the form of roll at the un-winder section, transport web through the process span 2, and finally wind it in the re-winder section. During this movement the web has to be maintained at constant tension and velocity. This system has a total of 3 spans. Each span is a section of web in the web handling system that is maintained at a certain tension based on the process requirement. Typically some form of closed loop tension control system is applied to maintain the tension. As shown in fig 4.3.1(c), the tension of a given span is measured with the aid of load cells and fed back to a controller which may be PID, fuzzy or others. The controller based on error in the tension sends control output to the servo pack which applies the appropriate torque to the driven rolls. A dancer is a prime mover driven mechanical system that is often used to control tension in a span in which the tension cannot be controlled using the conventional model in 4.3.1(c). Such as, when running a sequential multi-color printing operation, the gravure rolls at the entry and exit of a span are electronically geared to

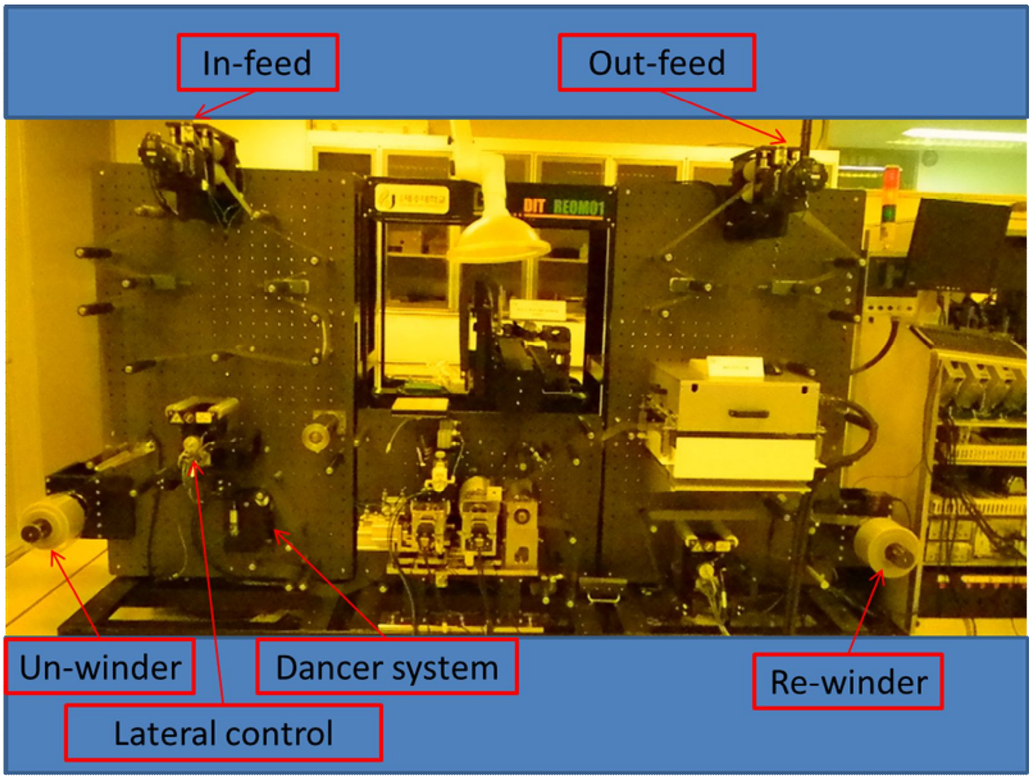


Figure 3.3.1(a) R2R system

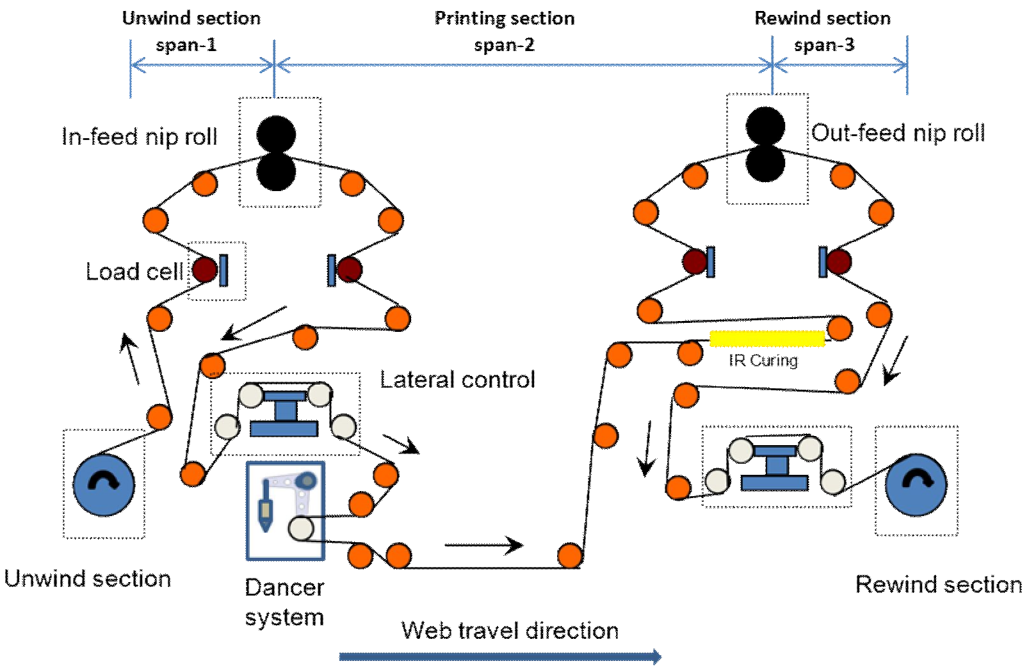


Figure 3.3.1(b) Schematic representation of R2R system

each other to operate at the same speed. Under these conditions a dancer system releases or withdraws web into the web span, thus controlling the tension. The dancer system can be seen in figs 3.3.1 (a) and (b).

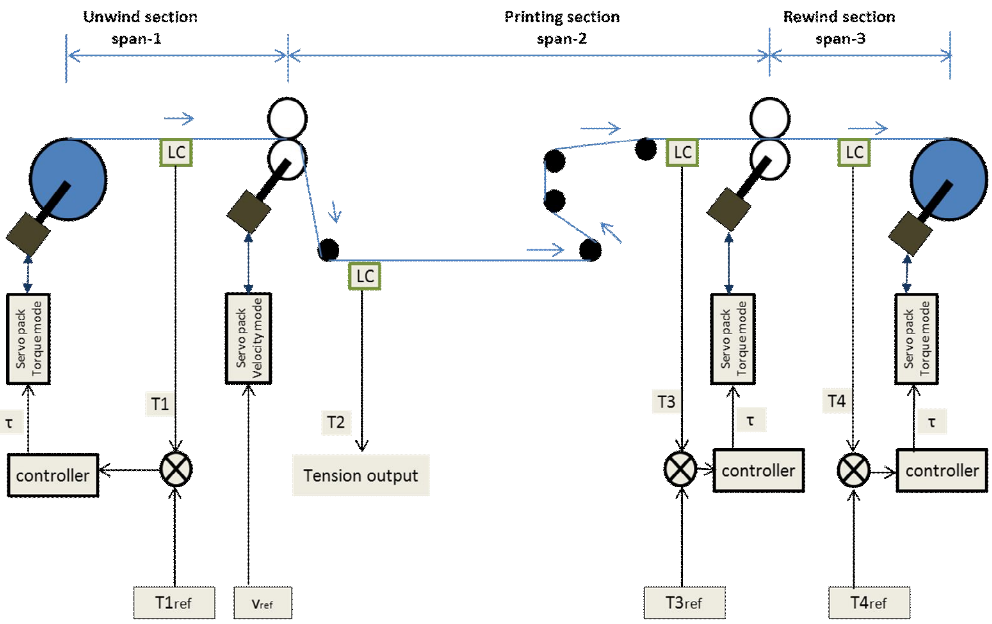


Figure 3.3.1(c) Conventional control architecture without dancer

In this paper a dancer system has been introduced into the R2R system and has been used to control web tension. The key feature of this work that distinguishes it from existing literature is that it does not use a system model to develop the control system. A fuzzy controller has been used. First the problem is turned into a position control problem and then the appropriate fuzzy logic based accurate position control system is developed. Then based on the correlation between the position of dancer and tension of web a simple proportional control law is developed and used to achieve tension control.

3.3.2. Methods and materials

3.3.2.1. R2R system

The R2R system is composed of 4 servo-motors. Servo pack used is Mitsubishi-MRJ2S70A. Tension feed-back is given by load cells (Magpowr-cantilever load cell). Interface with R2R system is done using National Instruments hardware. Entire algorithm has been written in the graphical programming environment, LabVIEW.

3.3.2.2. Dancer system

Dancer system is built specifically for R2R system as can be seen in fig 3.3.2(a). It has a pneumatic cylinder for prime mover and a potentiometer-Copal (J50S 20K) to sense angular rotation as seen in fig 3.3.2(b). The potentiometer measures angular position of the dancer in terms of 0-5 Volts. Although range of potentiometer is 0-5Volts the true range of rotation of the dancer is only 5.6° and hence correspond to 3-3.25V. For convenience angle is measured in Volts in this section. The force is transmitted from the pneumatic cylinder-Fujikura BF cylinder (FCS-25-26-S1) - to the idle roller of the dancer system via an "L" shaped dancer link shown in fig 3.3.2(b). Pneumatic pressure is applied to the cylinder through a proportional pressure regulator-Norgren VP12-which is capable of producing a pressure from 0-8bar proportional to the applied analog signal ranging from 0-10V. The free body diagram of the forces acting on the dancer is shown in fig 3.3.2(c). F is the force exerted by the cylinder and F' is the total force exerted by the web tension T on the dancer link.

3.3.3. Control system design

Control system for the given system already exists as shown in fig 3.3.1(c). But it can be seen that span-2 is quite long and there are two load cells on it. It was found that the tension in the load cell on span-2 closest to span-1 showed a significantly lower tension than that used in feed-back loop of span-2 tension controller. The tension control loop for span-2 is on the downstream end of the span. The large length of the span and the low tension used may be the reason for this phenomenon. The goal is to control the tension in the initial portion of span-2 using the dancer system. Although tension in a moving web is a very complex process it can be simplified as follows:

Young's modulus

$E=\sigma/\varepsilon$

Where, σ= Stress on web

ε=Strain in web

$\sigma = T/A$

$\varepsilon = \delta l / l$

where,

T=web tension

A=area of cross section of web

L=length of span

Therefore,

$T \propto \varepsilon$ ……………………….(3.3.1)

The dancer system operates by controlling this strain. And strain control is simply a matter of positioning the dancer arm. Although the relation is not this simple, as the material property of the web is not linear as shown, but equation (3.3.1) is assumed to be true. There are other sources of non-linearity such as the motion of the dancer system. The idle roller in the dancer travels along an arc but it is assumed to travel along a straight line as the angle moved is small. Similarly, the force exerted by the cylinder is non-linear especially when the signal is varying, as with all physical systems it will have delays in response.

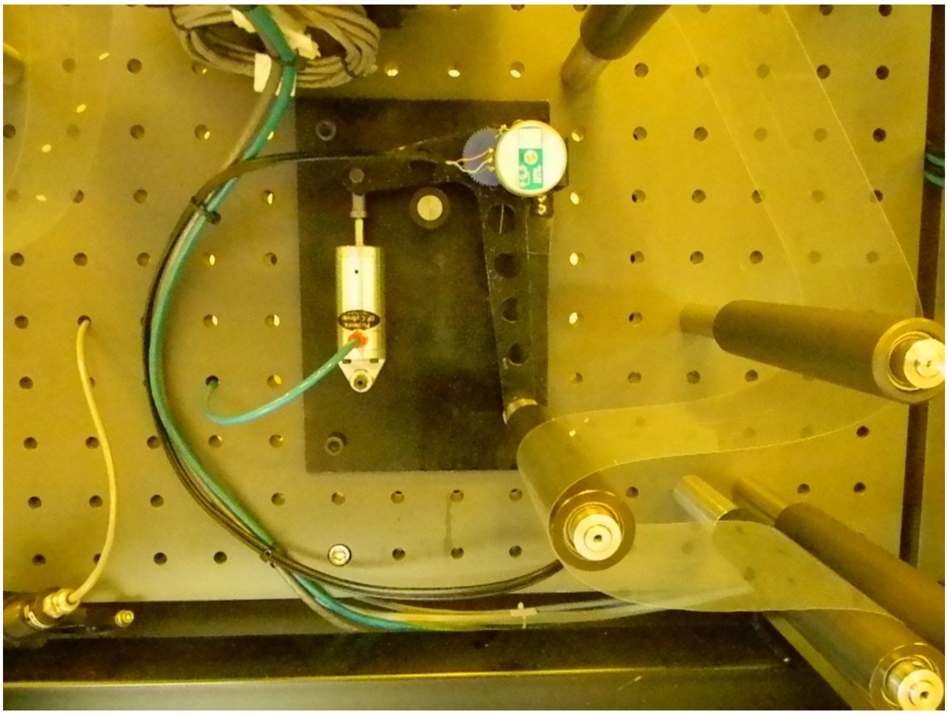


Figure 3.3.2(a). Dancer system

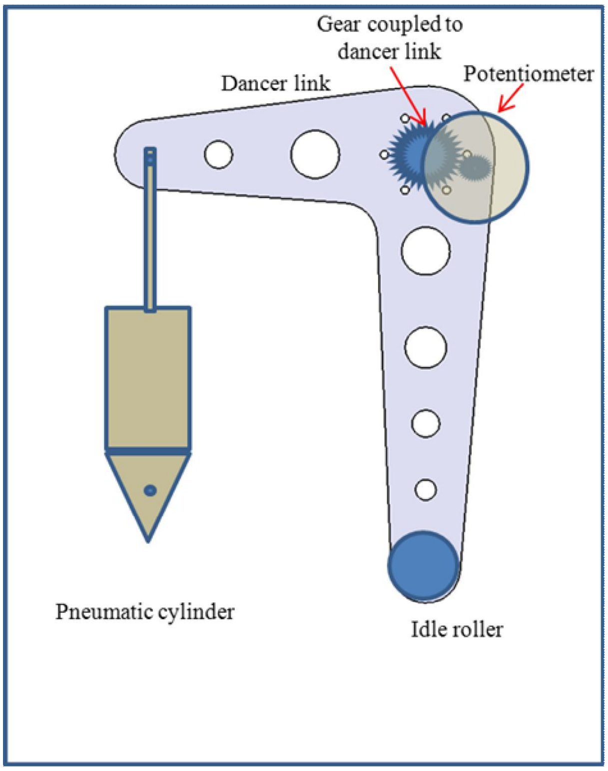


Figure 3.3.2(b). Components of dancer system

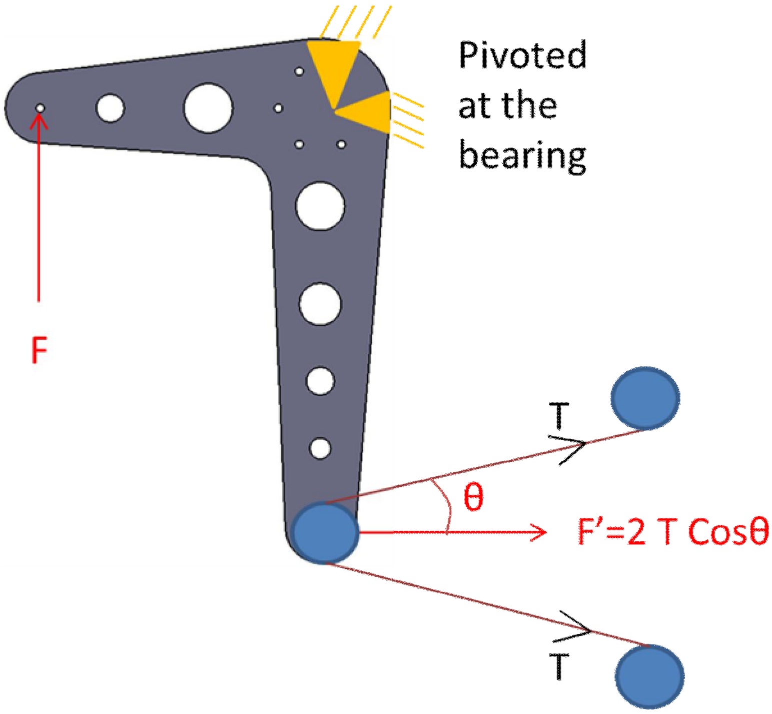


Figure 3.3.2(c) free body diagram of dancer link

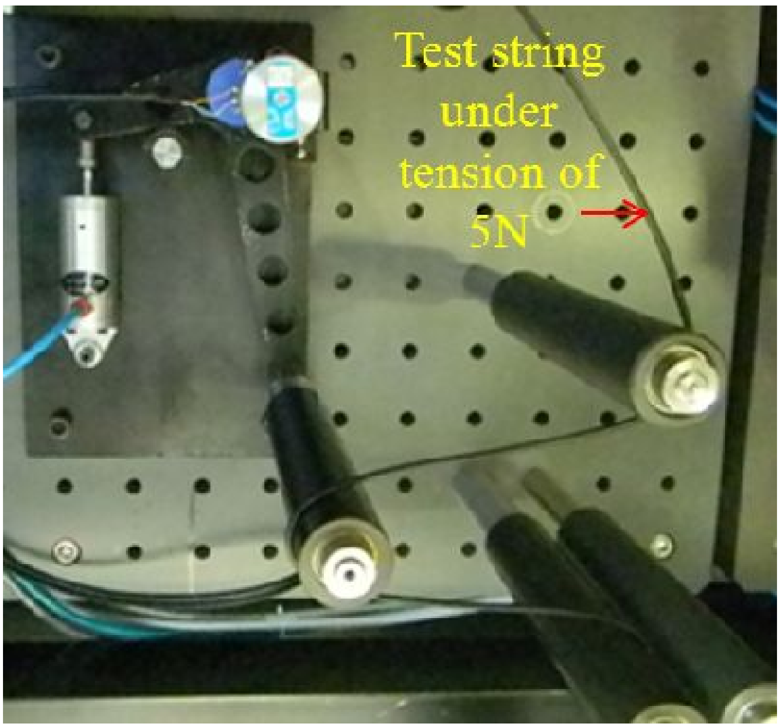


Figure 3.3.3 Test rig with standard tension of 5N

3.3.3.1. Fuzzy position control

A test rig is set up as shown in figure 3.3.3. The web is replaced with a string that maintained a constant tension. This tension is also the reference tension. This is achieved by hanging a weight equivalent to 5 N, i.e. 500gms at the end of the string that traces the path followed by the web in the dancer system. As mentioned earlier the whole dancer system is highly non-linear and we need to achieve perfect position control. Again for convenience we shall refer to position in volts as given by potentiometer, and the pressure is also expressed in volts. First the voltage is slowly increased until the pressure in the cylinder just begins to pull and move the string under tension. This is found to be 2.75volts. Now the tension is slowly decreased until the string is able to pull the dancer system, this value was found to be 1volt. Ideally both of these values have to the same, but due to inertia, friction and a host of other reasons they are distinct. These two values form the basis for a fuzzy control system. The fuzzy controller takes error in position, given in volts as input and computes an output voltage for proportional pressure regulator in the range (1, 2.75). The overall fuzzy controller is given in fig 3.3.4. The output from the output scaling function is given as,

η=K1*(output of fuzzy inference system)+K2 ……………………………………….(3.3.2)

From the range of the function which is (1, 2.75) and range of the fuzzy inference system we can compute K1 and K2. Hence

η=-0.875*(output of fuzzy inference system)+1.875 ……….…………………….(3.3.3)

The input scaling function is given as

μ=ep/K3…………………………………………………………….………………….(3.3.4)

where ep=Pref-P

where, Pref=reference position or the position where the dancer link should be; and, P=actual position of dancer.

K3 is to be determined experimentally.

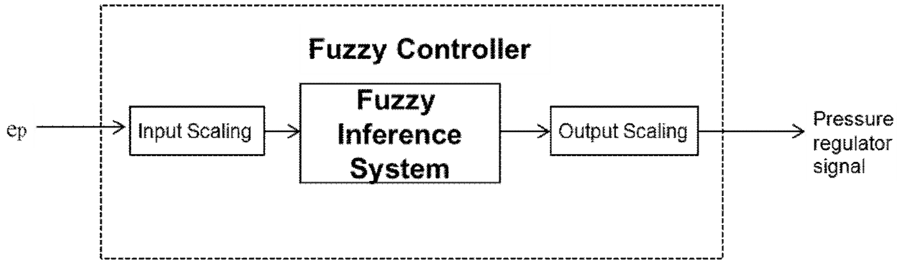


Figure 3.3.4 Fuzzy controller

The fuzzy inference mechanism is described by fig 3.3.5(a) and (b). Fig 3.3.5(a) is used to find member ship value of each of the sets given in it. Fig 3.3.5(b) is used to compute the output of individual rule, which are given as follows:

If VL then VH
If L then H
If N then N
If H then L
If VH then VL

The final output of the fuzzy inference mechanism is found using the center of gravity method. The output is given by

$$t=VL(\mathrm{ep})*1+L(\mathrm{ep})*x+N(\mathrm{ep})*0+H(\mathrm{ep})*(-x)+VH(\mathrm{ep})*(-1) \quad \text{.....................................(3.3.5)}$$

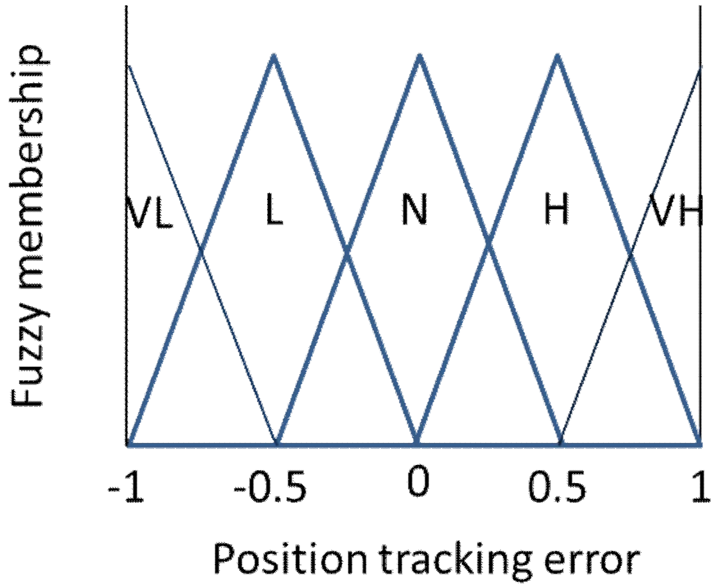
This is a very simple fuzzy controller, but non-linearity can be introduced into this controller. The controller has two tuning parameters K3 and x. After iteratively tuning the K3 and x values were found to be 0.07 and 0.85, respectively. The well-tuned fuzzy controller is operated to determine its capability, by giving it step input Pref values of 3.15, 3.2 and 3.25, as shown in fig 3.3.6.

3.3.3.2. Closed loop fuzzy tension control

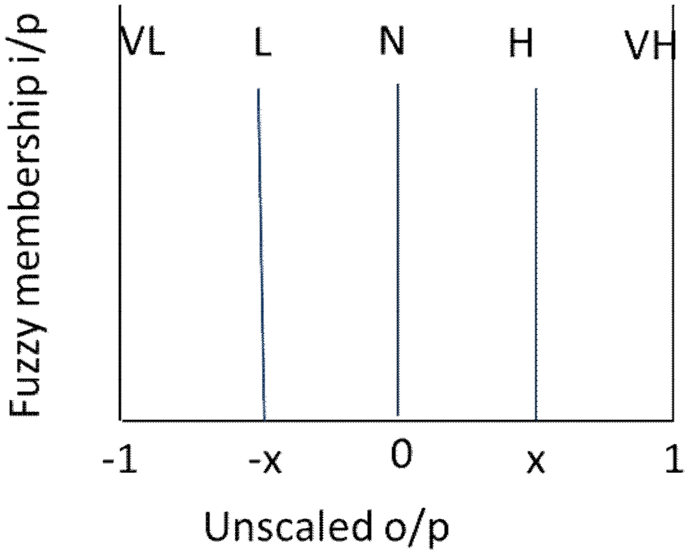
Due to the excellent closed loop position control, it is now possible to introduce closed loop tension control. The string is removed from the dancer system and the actual web is introduced into it. The final closed loop tension control is implemented as shown in fig 3.3.7. To achieve it the fuzzy controller is slightly modified. The *Pref* in equation (3.3.4) is given by

Pref=Kp*(Tref-T) ……………………………………………………………..(3.3.6)

Equation (3.3.6) is actually a proportional control. Where, Kp is experimentally determined to be -15.



(a)



(b)

Figure 3.3.5 Fuzzy sets; (a) input set (top); (b) output set (bottom).

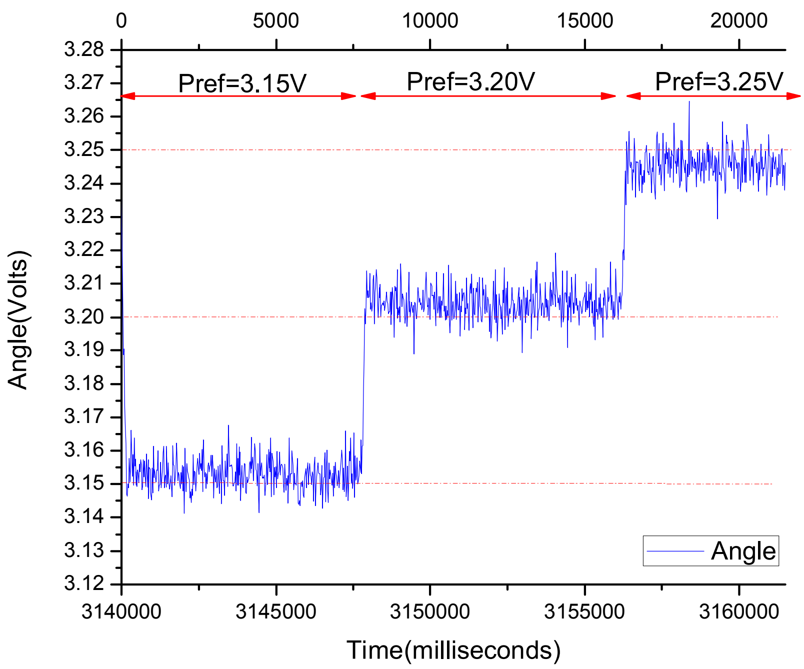


Figure 3.3.6 Step response of position control

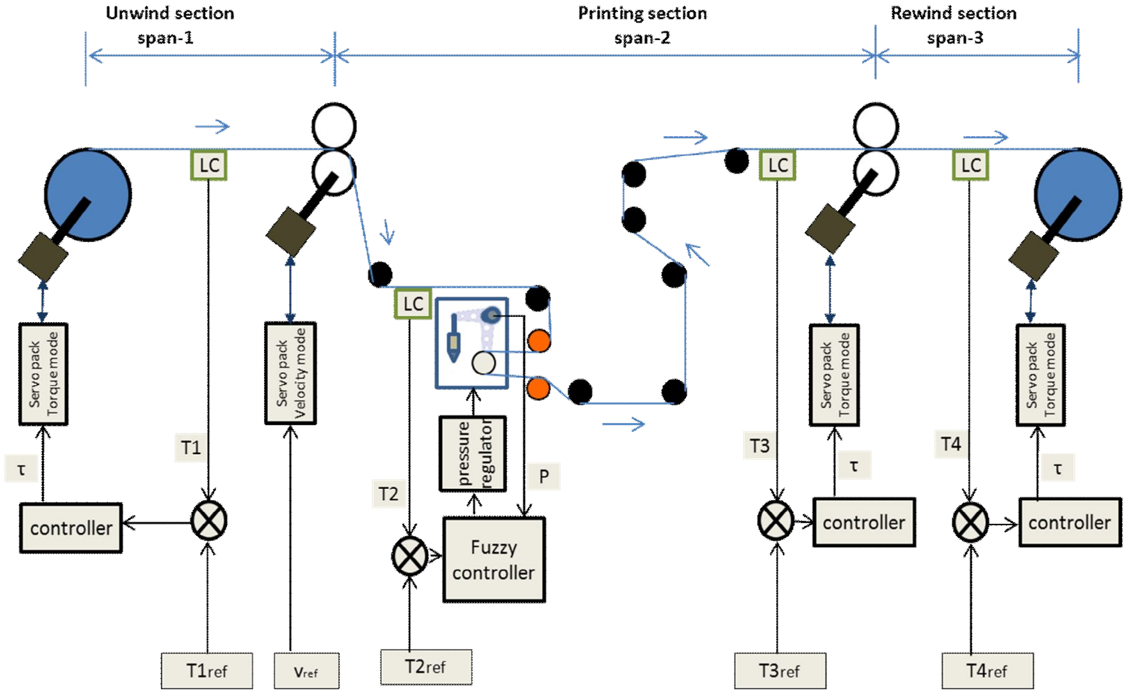


Figure 3.3.7 Closed loop tension control using dancer

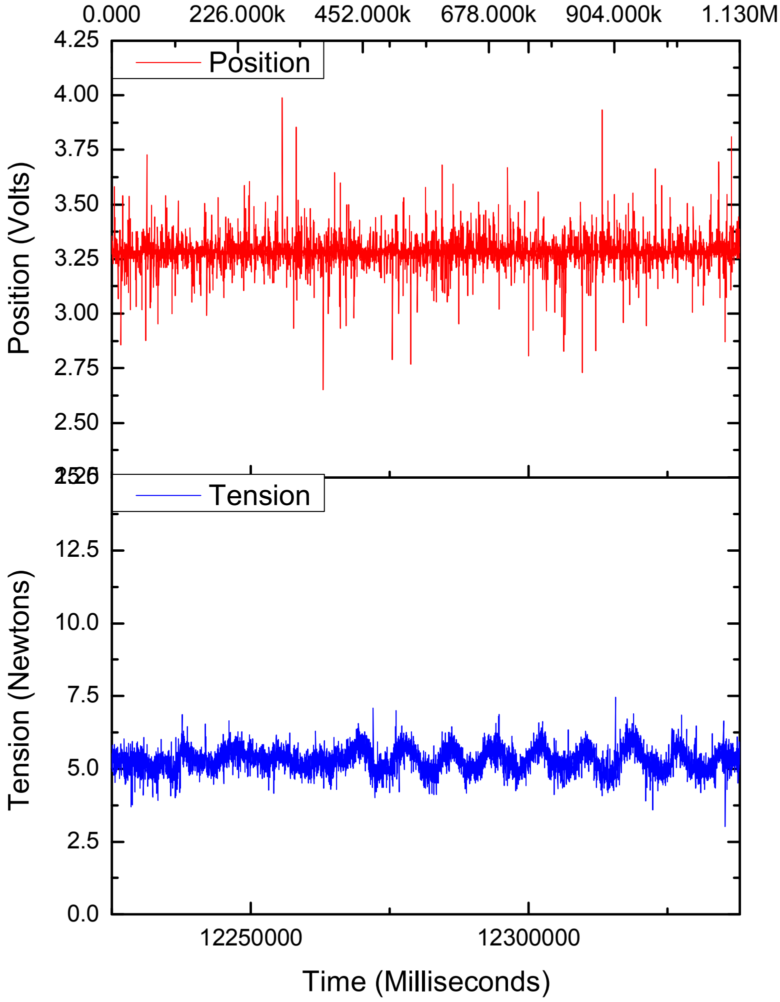


Figure 3.3.8 Closed loop tension characteristics of the fuzzy dancer control system

3.4. Slot die coating

Poly (3,4-ethylenedioxythiophene)-poly (styrene-sulfonate) (PEDOT:PSS) was coated on flexible polyethylene terephthalate (PET) substrate using slot die on a roll-to-roll (R2R) system under different web tensions. The electrical resistance, the standard deviation of the recorded resistance and surface roughness of the coating under different tensions were analyzed. Based on these data an optimum tension was determined for operation of the R2R system for slot die coating. A new image processing based method was adopted to quantitatively measure the proportion of peaks to the valley like features seen in the SEM images of the coatings. Based on this a relation between resistance and the surface texture has been observed.

3.4.1. Introduction

Slot die process is a technique to mass produce coatings on flexible substrates. It has found application in a variety of industries such as printing, laminating, printed electronics etc. Its application in printed electronics is comparatively recent. The Equipment used in this work is shown in Fig. 3.4.1(a). It is known as the roll-to-roll (R2R) system or the web handling system. Purpose of the R2R system is to transport the substrate (web) through the slot die coating system at constant velocity while maintaining a constant tension on the web. The schematic representation of the R2R system is shown in Fig. 3.4.1(b). It can be seen that the web is un-wound at the un-winder in span-1, it travels through the lateral control system followed by the slot die coater and Infra-red (IR) dryer in span-2 and finally re-wound in span-3. All the while the web tension is tightly controlled. From the process perspective, the control of web tension has always been regarded as the most important aspect of R2R system based production. The key aspect of this technique is that it can coat a flexible substrate continuously in the form of stripes in the direction of substrate motion. The width and spacing between these stripes is determined by the die that is inserted into the slot die coating apparatus shown in Fig. 3.4.2. Another advantage of this method is that the thickness of the coating can be controlled almost perfectly by adjusting the concentration of the ink, the flow rate of the ink and web velocity.

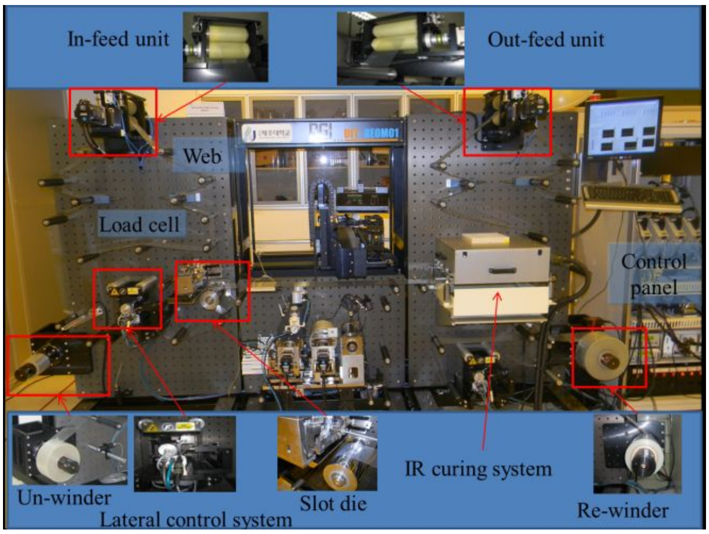


Figure 3.4.1(a) R2R system

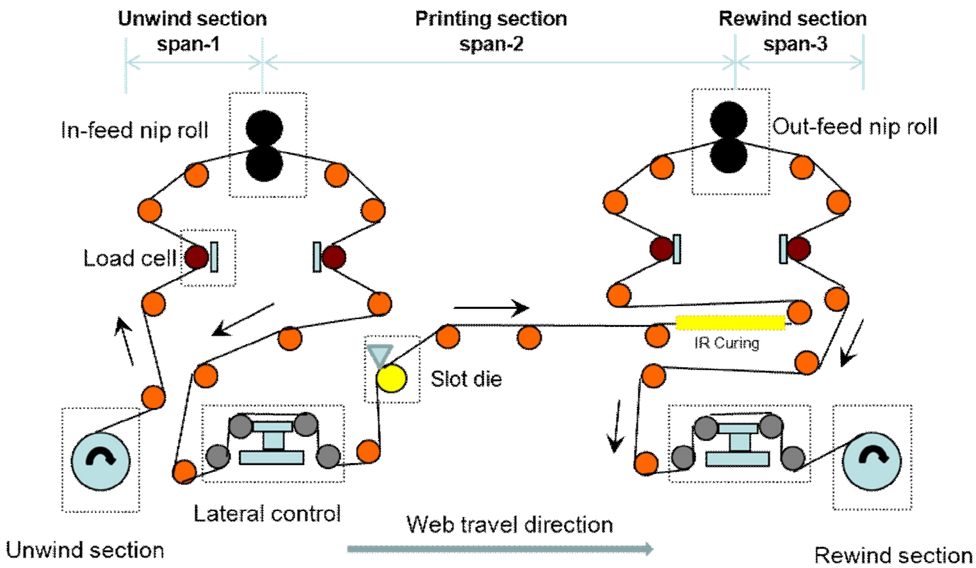


Figure 3.4.1(b) Schematic representation of slot die coating system

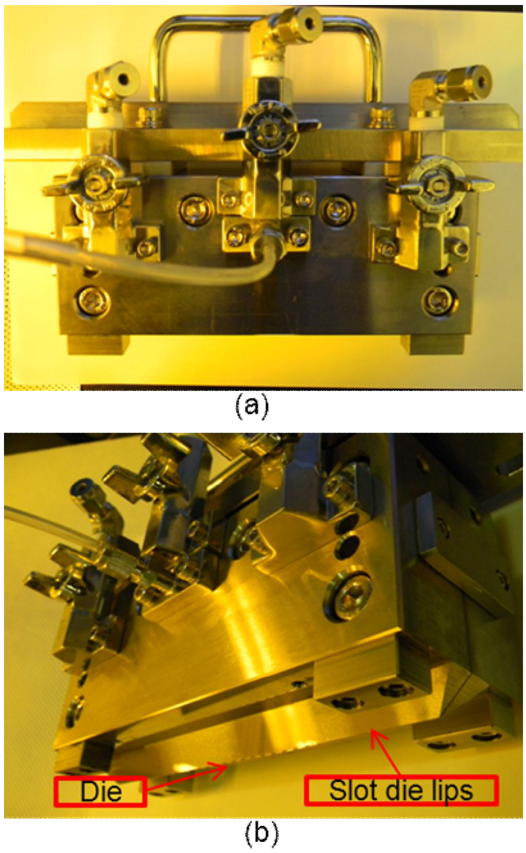


Figure 3.4.2(a) Front view of slot die; (b) View of slot die lips and the tip of the die

In this paper the sheet resistance of PEDOT: PSS coating has been studied with respect to change in web tension during processing. Similar study in offset printing has revealed that the change of web tension has a significant effect on the interaction between the web and the ink. There is a need for a study that relates web tension to sheet resistance in slot die coating, as sheet resistance is the ultimate performance measure of a conductive coating/electrode in a printed device not thickness or roughness. This paper addresses this need by printing the conductive polymer PEDOT: PSS on a PET substrate using slot die coating with the web being maintained at various tensions. During this study image processing techniques have been used to enhance the insight into the electrical properties of the conductive coating.

3.4.2. Materials and methods

3.4.2.1. Formulation of PEDOT:PSS ink

Formulation of PEDOT: PSS ink was done by using 3:2 ratio of PEDOT:PSS diluted with isopropyl alcohol and continuously shaken for 5 h using a mechanical shaker. The obtained solution was kept undisturbed for half a day and the clear solution is separated by decantation and then filtered using polymeric filter to achieve homogeneous dispersion. The viscosity and conductivity of formulated ink were found to be 125 *mPa.s* and 7.00 *mS/cm* respectively.

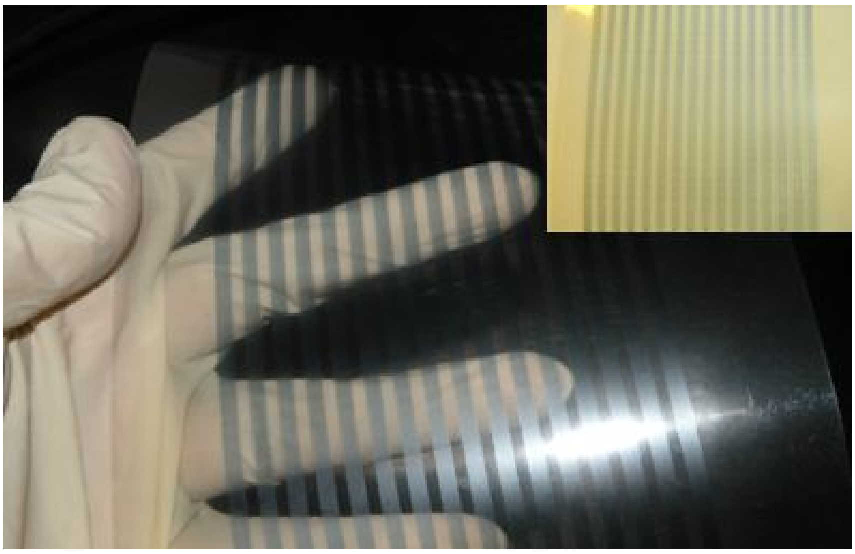


Figure 3.4.3 Photograph of PEDOT: PSS coated on PET substrate using slot die process.

3.4.2.2 Web Handling System and Slot Die

The web handling system along with the slot die is shown in Fig. 3.4.1. R2R system transports the PET substrate from the un-wind section to the re-wind section through the slot die. The width and thickness of the PET substrate are 120 mm and 0.1 mm, respectively. The slot die used for this experiment is shown in figure 3.4.2. It has a die that allows printing of patterns 3 mm wide and 2 mm apart. This die enables us to make 16 such parallel patterns as shown in Fig. 3.4.3. The ink from a positive displacement pump is pumped at a constant rate into the slot die setup. Slot die is a precisely machined ink dispensing unit that issues ink onto the web moving underneath it. It is widely preferred because of the simplicity of the whole process and because it is a non-contact process.

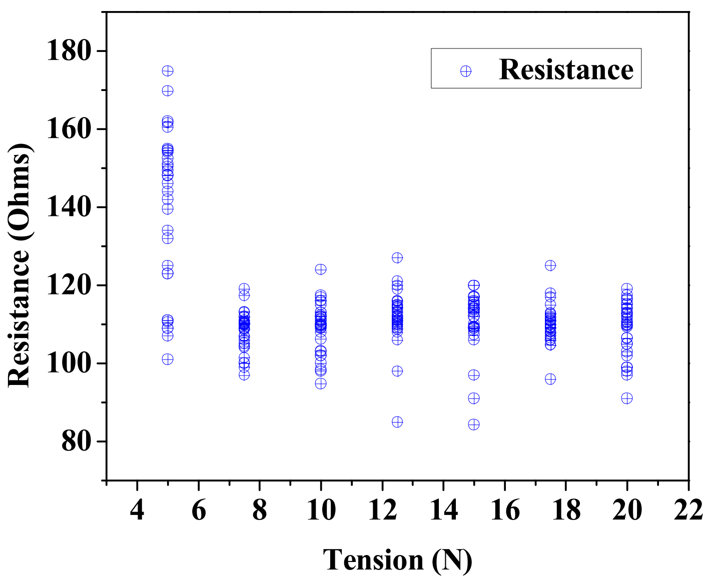


Figure 3.4.4 Resistance vs. tension plot.

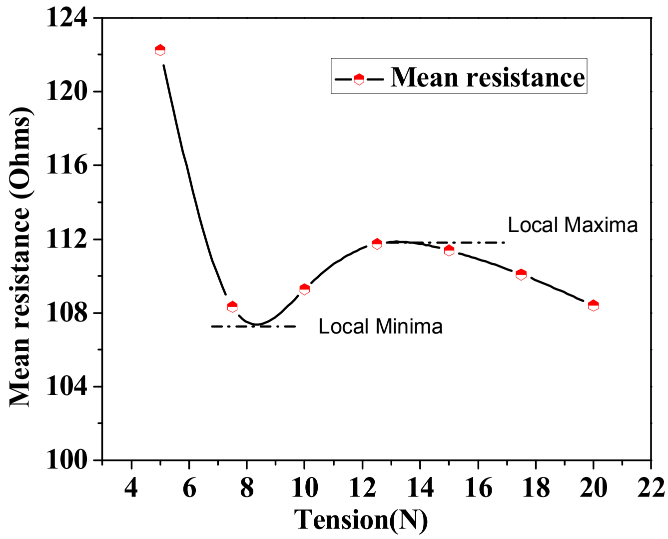


Figure 3.4.5(a) Mean resistance vs. tension.

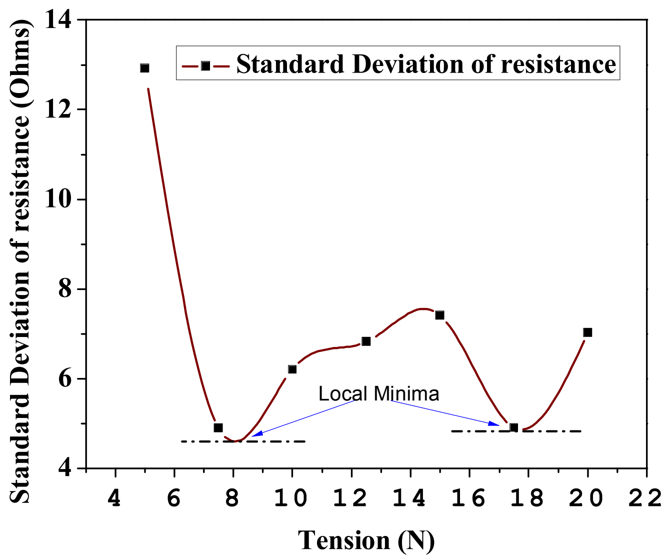


Figure 3.4.5(b) Standard deviation of resistance vs. tension.

3.4.3. Experiment design

The objective of the experiment is to understand the relation between the web tension and the resistance of PEDOT: PSS ink coated on PET substrate for a constant flow rate of ink flowing into the slot die. For this purpose the flow rate of positive displacement pump is kept constant at 13.3 ml/min. Typically there is a lower limit below which the coating is non-uniform, the set flow rate was just above this value and was arrived at by iteratively raising the flow rate from zero. The velocity of the web was maintained at 0.012 m/s. During the initial adjustments to achieve a uniform coating the web tension was set at 5 N. This value is the minimum stable tension capability of the R2R system. Also it is important to maintain the minimum possible tension during the processing stage as subsequent removal of tension is bound to cause contraction of the web. Once steady state coating is achieved the web tension is incremented in steps of 2.5 N up to a maximum of 20 N. The amplitude of noise in the tension is less than of 0.5 N. This noise value tends to be a constant for all set tensions. Soon after the slot die coating, the web enters IR curing unit maintained at 120 °C.

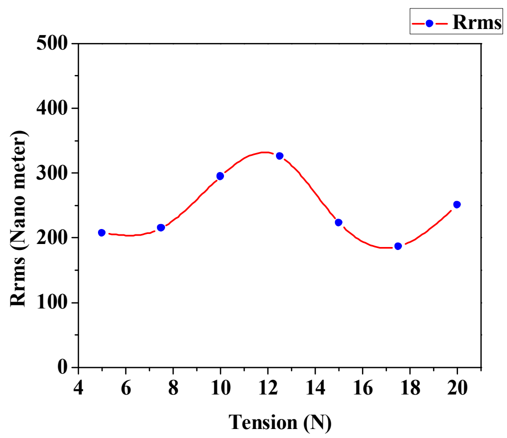


Figure 3.4.6 Surface roughness vs. tension

3.4.4. Results and discussion

3.4.4.1. Resistance

The results from the experiments were analyzed with respect to the resistance of the coating. The sheet resistance was measured for each of the samples that were obtained by operating the R2R system at the 7 different tensions. Resistance was measured using the four point probe at different locations on the surface of the pattern and the plotted as shown in fig. 3.4.4 and it revealed significant changes with respect to tension. To interpret this data, statistical techniques were used and the mean (μ) and standard deviation (σ) of resistance corresponding to each tension is found and plotted in Fig. 3.4.5 (a) and (b) respectively. Statistically σ is a measure of the variation about the mean. The resistance range $\mu \pm 3\sigma$ will account for 99.7% of the sampled population. Therefore it can be a useful tool to optimize the tension to achieve desired pattern resistance.

From Fig. 3.4.5 (a) and (b) the relation between tension and resistance and standard deviation of resistance were found to be highly nonlinear. As seen in Fig. 3.4.5(a) the resistance first decreased as tension was increased from 5 N and reached local minima at around 8 N. From 8 N onwards the resistance increased and reached local maxima at around 12 N and decreases till 20 N. When examining the standard deviation of resistance in Fig. 3.4.5(b), it can be seen that there are two local minima; one at 8 N and the other at 17.5N. The quality of a conductive coating can be determined using two criteria. First, conductive electrodes should have the least possible resistance. Second, the resistance should be as consistent as possible. Standard deviation is a good measure of consistency. The lesser the standard deviation lesser is its variation about the mean resistance. There are two local minima points in the standard deviation plot and 8 N is the optimum tension for the process, because it coincides with the minima of the web resistance. There may be other optima if tests were done at higher tensions as is evident from the highly non-linear relation of resistance and the standard deviation of resistance with the web tension. But it is always advisable to apply the least possible tension while printing on a flexible substrate as the internal stresses is also bound to increase with tension. Following the above optimum tension it should be possible to make coatings with a resistance of $107 \pm 13.5\ \Omega$.

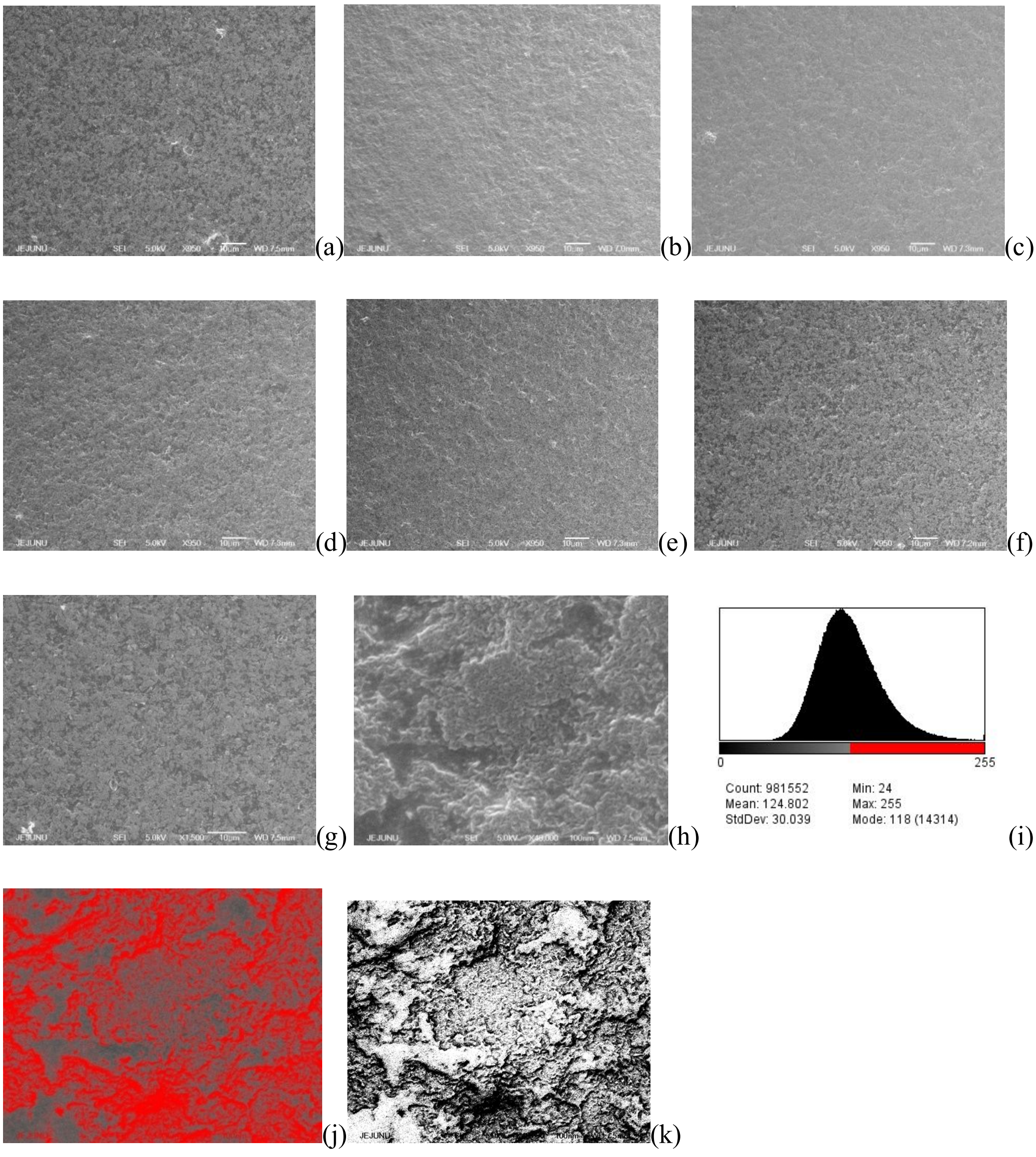


Figure 3.4.7 SEM images of coatings made at different tensions: (a)Tension=5N; (b)Tension=7.5N; (c)Tension=10N; (d)Tension=12.5N;(e)Tension=15N;(f)Tension=17.5N;

(g)Tension=20N; Image processing:(h) SEM image of a sample at 40000x magnification;(i) Frequency histogram of the image(j) Thresholding process, red pixels indicate peak, while black pixels indicate valley;(k) Black and white image after thresholding.

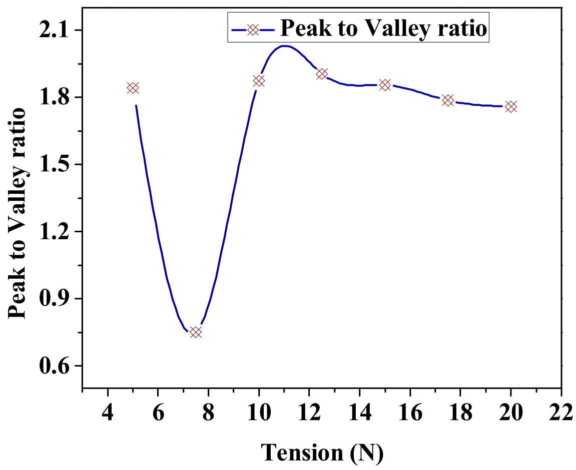


Figure 3.4.8 Peak to valley ratio vs. web tension

3.4.4.2. Surface characterization

In view of the considerable variation observed in resistance it is worthwhile to study the surface and microstructure of the coating. It has been reported that surface forces between the web and ink are affected by tension. These should inevitably have an effect on the surface roughness as shown in Fig. 3.4.6.

Image processing techniques can be used to find quantitative measure of features that are recognizable on an image by human eyes. Fig. 3.4.7(a)-(g) show the scanning electron microscope (SEM) image of the coating made under different tension. Fig. 3.4.7(h) is one of those images examined closely. The histogram of the image can be seen in Fig. 3.4.7(i). It can be distinctly seen that there are smooth valleys in darker shade and peaks that have a mesa like structure which are somewhat rough and brighter. For convenience we shall refer to these formations as valleys and peaks respectively. In this paper image processing techniques will be used to quantitatively measure the influence of peak like features that are seen on the surface of the PEDOT:PSS coating. The SEM images were gray scale images. This means that the image was made up of pixel units that represent brightness of a point on a scale of 0-255. Thresholding is a process whereby the gray scale image can be converted into a black and white image by setting a threshold value such that all the pixels within this threshold were converted to a brightness of 0, and the remaining were converted to a brightness of 255. As seen in Fig. 3.4.7(j), the threshold of the image in Fig. 3.4.7(h) was adjusted such that all the peaks and valleys were separated. The peaks can be seen in red color while valleys are black in color. After the thresholding process the final black and white image looks as can be seen in Fig. 3.4.7(k). Now the pixels corresponding to the peaks and valleys can be easily counted. Each pixel contributes to the area of the image, thus the number of pixels in a feature was directly proportional to the area of that feature. Here a new term is defined, called the peak to valley ratio given as follows:

η= Number of pixels corresponding to peak / Number of pixels corresponding to valley…..(3.4.1)

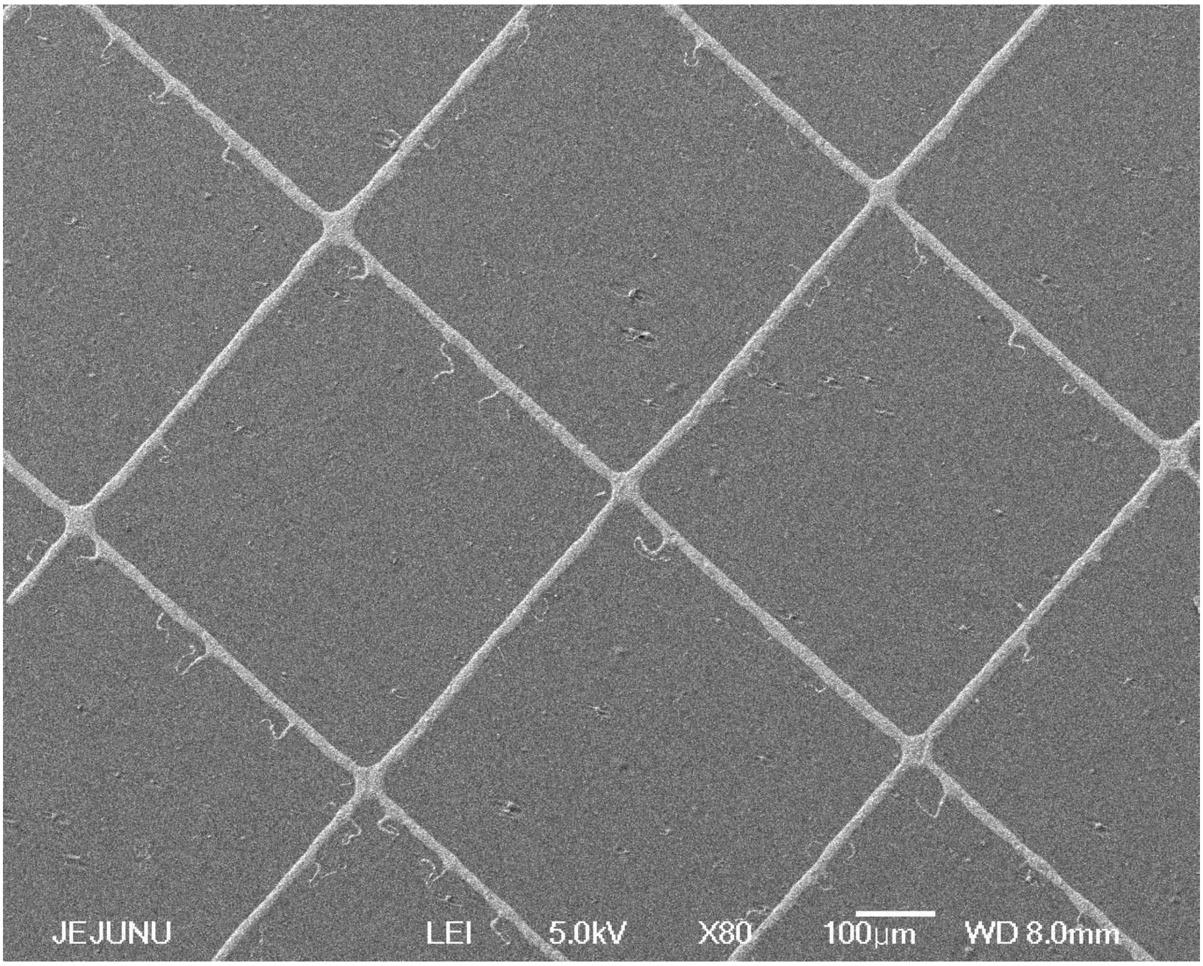
The same process was repeated for all the images in Fig. 3.4.7(a)-(g) and their *η* values were calculated. The plot between the peak to valley ratio and web tension was as shown in Fig. 3.4.8.

Comparison of the plot of peak to valley ratio (*η*) and resistance against tension suggests a strong relation between the two as they show similar trends. Comparing Fig. 3.4.5(a) and 3.4.8, it can be said that the as tension is increased from 5 N to 7.5 N, both *η* and the resistance values decreased followed by a rise. Also in the range 12 N to 22 N both values fall steadily. Thus it can be said that *η* is a function of tension. And *η* has a strong contribution to the resistance. Heuristically it can be stated that as peak features increase the resistance also increases and that peaks probably don't or contribute to a lesser extent to the conduction of electrons compared to the valleys.

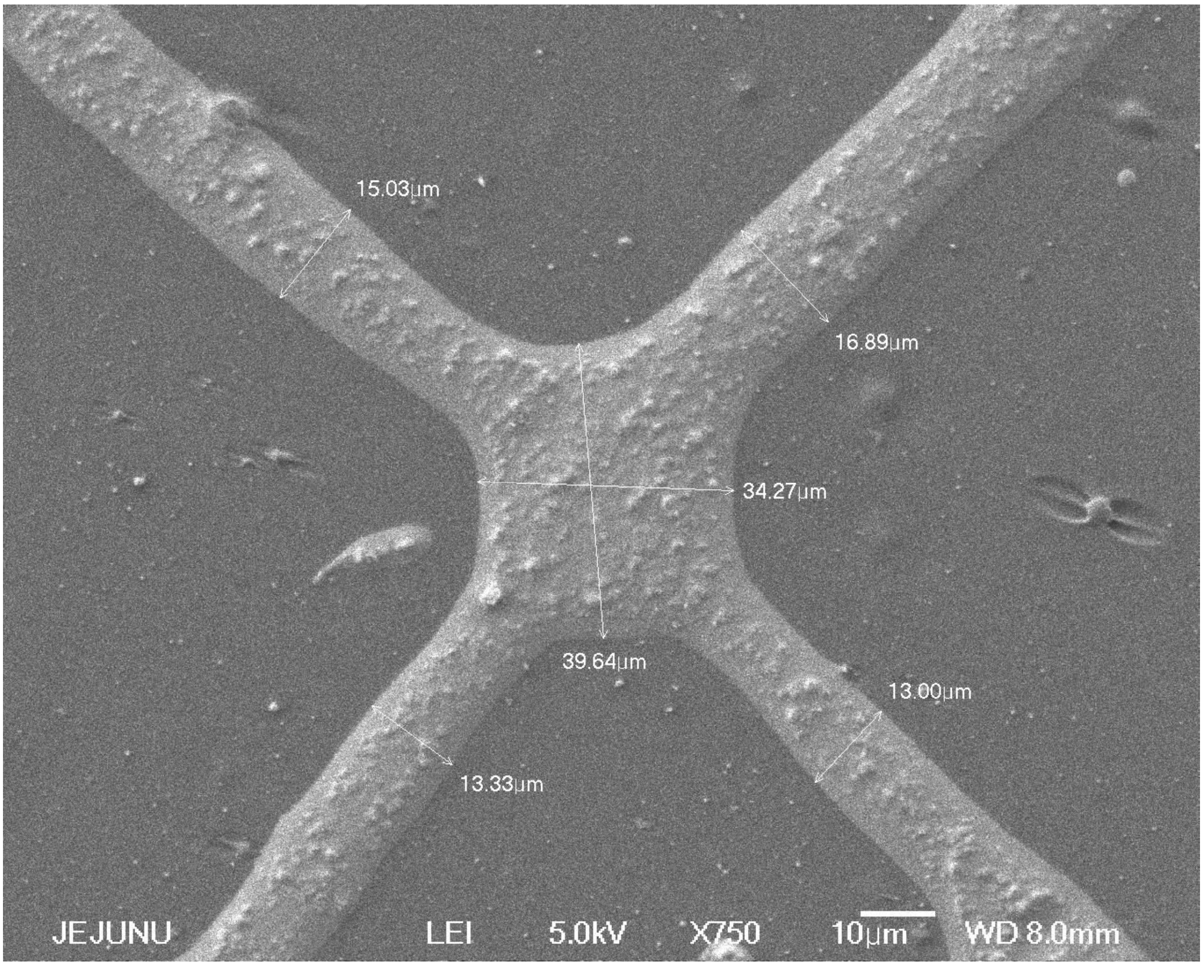
4. Fabrication of products on R2R system

4.1. Offset printed products

As stated in section 3.1 gravure offset printing was done on R2R system to fabricate silver patterns. The gravure roll had patterns for several different devices such as thin film transistor, solar cell mesh etc. The mesh patterns were found to be most perfect among these. The purpose of these mesh patterns is to device use as conductive paths for transparent conductive electrode. Usually the conductive polymers are used as the transparent electrodes. The mesh in this case was used to provide a parallel conductive path so as to lower the net resistance of the coating. Therefore the mesh patterns were coated with PEDOT: PSS polymer. This decreased the overall resistance of the polymer by 22%. The SEM image of mesh is shown in figure 4.1 (a) and (b). It can be seen that the mesh pattern is not perfect. There appear to be small branches to the pattern line. These could have happened during transfer of ink between the gravure offset and the substrate. In fact upon closer examination it can be seen that there is a few micron variation in thickness of the patterns. And also the intersection between the pattern lines is not sharp. There appears to be an aggregation at the junction. This is possibly because of surface forces. In figure 4.2 the SEM image of PEDOT: PSS coated mesh can be seen. The thickness of the mesh and coating were found to be 3um and 300nm respectively.

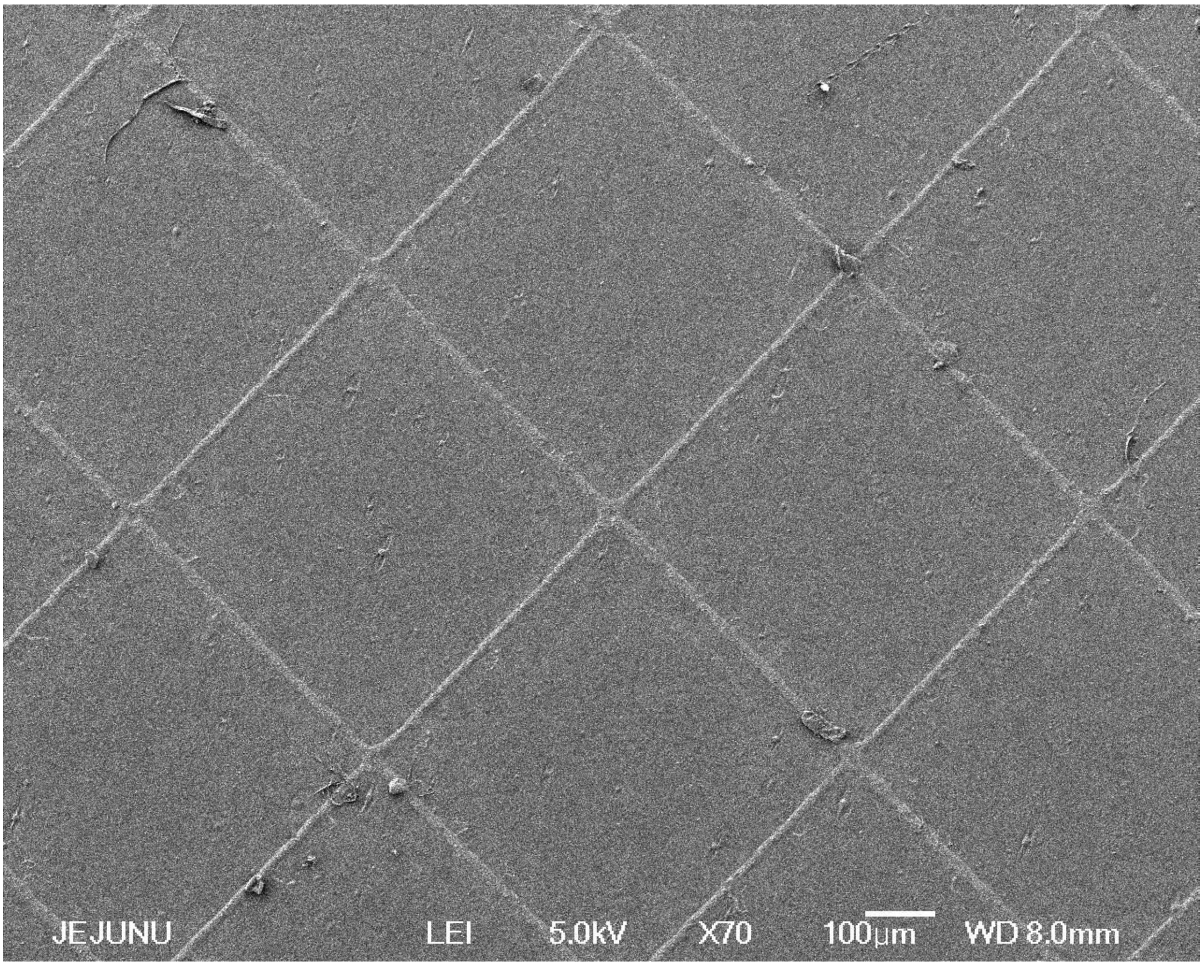


(a)

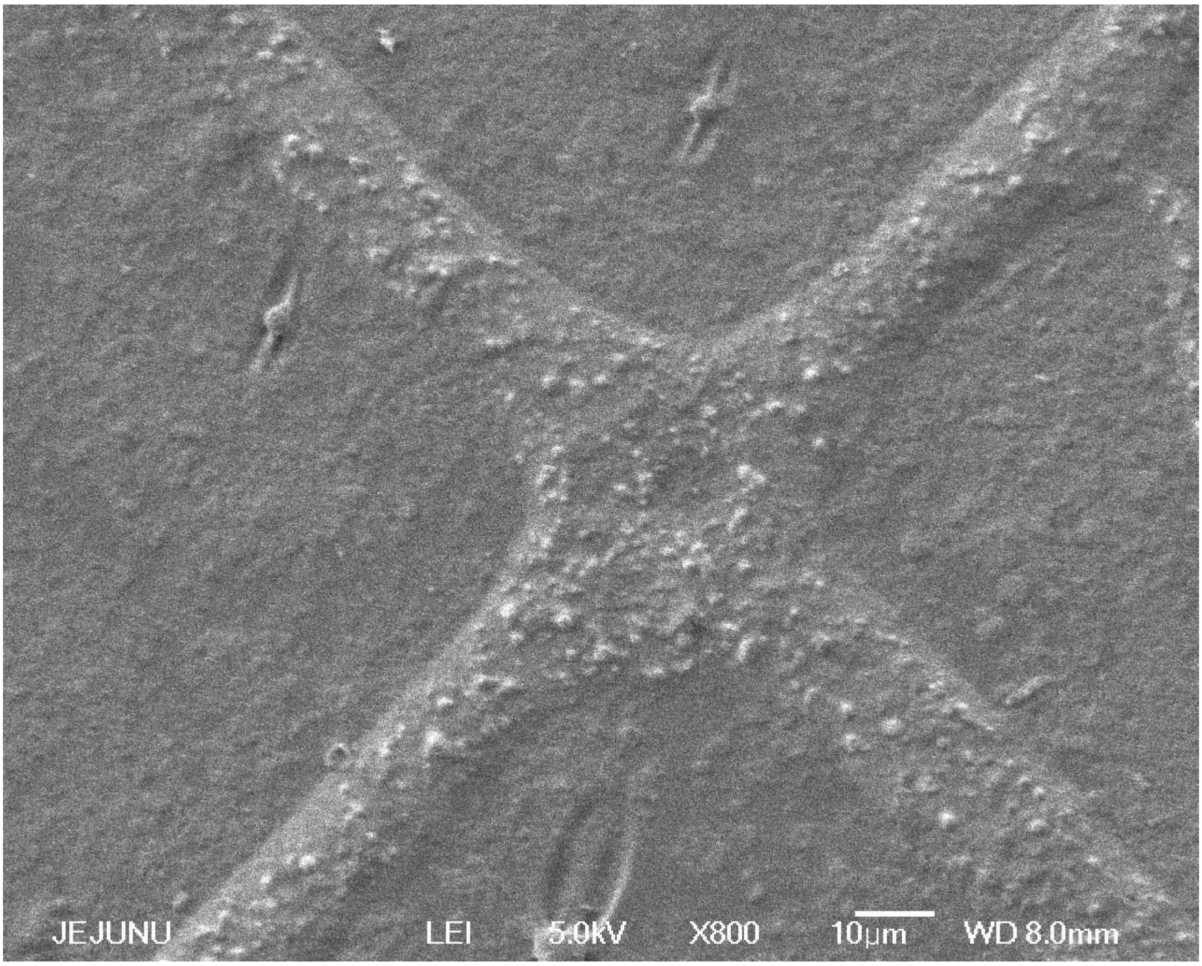


(b)

Figure 4.1 (a) SEM image of mesh pattern; (b) SEM image of junction of mesh pattern.



(a)



(b)

Figure 4.2 (a) Mesh pattern coated with PEDOT: PSS; (b) Junction of the mesh with coating

4.2. Slot die coating

Slot die coating has been described in detail in section 3.4. The PEDOT: PSS stripes shown in figure 3.4.3 are 3 mm wide and 2 mm apart. Figure 4.3 shows AFM image of the coating. It can be seen that the surface is quite uniform.

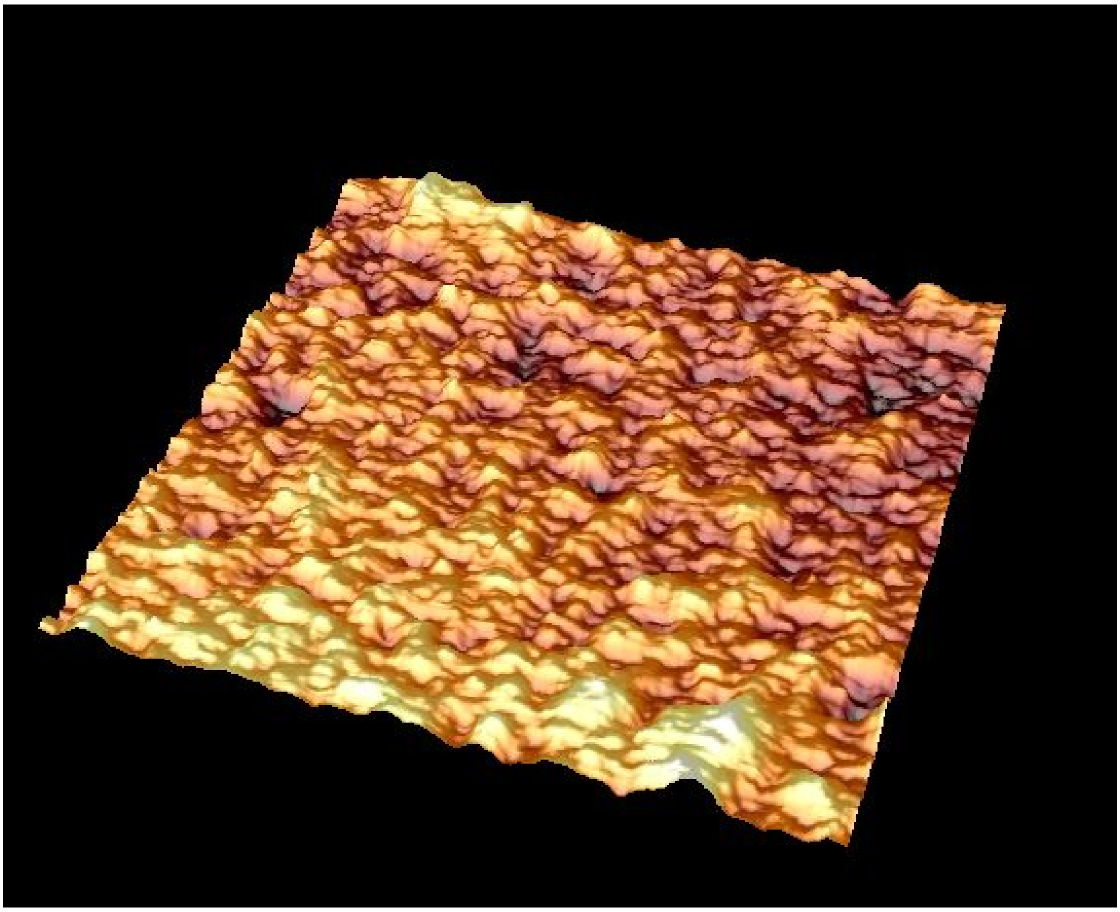


Figure 4.3 AFM image of PEDOT: PSS coating

5. Results and discussion

5.1. Offset printing

As elaborated in section 3.1, the newly proposed algorithm for continuous offset printing was developed and used to operate the R2R system at a speed of 0.04m/s with a reference tension of 5N. As a result disturbances to the web tension are reduced considerably. As per tension guideline in section 2.5, the reference tension for PET material of 0.1 mm thickness and 110 mm width is a minimum of 60.67 N, but the reference tension used here is 5 N in order to keep the strain in the web to a minimum. By industry standards the tension can vary up to 6.06N from the reference tension. The standard deviation and mean of T2 were found to be 1.044572 and 5.20082 N, respectively. This when viewed statistically means that for most part the web tension is 5.2008±3.133716 N, thus satisfying the industry standards. The overshoot in tension T2 reduced from 15N to 8N. The tension used for printing is very low, almost 8.3% of the lowest recommended tension. The reduction in disturbances in the span 2 has also reduced the disturbances in span 3. This indicates that the said system reduces the flow of disturbances further downstream. The spikes in tension due to the said disturbances still exist but the tension immediately returns to the reference tension as can be seen in fig 3.1.10. The settling time after each of the disturbances is found to be less than 1second.

Due to the uniqueness of the problem and innovative nature of the solution it is difficult to compare the achieved result with any existing work. Also in this work the spikes in tension have been reduced to be less than 8.5N in amplitude. Further the amplitude of disturbances in known literature are almost sinusoidal in nature whereas in this work the disturbances are in the form of spikes that diminish rapidly as seen in figure 3.1.10. It implies that except for the close proximity of the spikes the tension amplitude is less than 1N.

5.2. Reduction of interaction between spans using fuzzy logic

Lateral control system requires some minimum tension to operate as mentioned earlier and printed electronics demands the minimum possible tension. A tension of 5 N is reasonable because it is found to be the least tension at which the given R2R system operates stably. This would be optimum if it was not for the disturbances produced by the offset printer. As can be seen in figure 3.2.7(a), the tension disturbance amplitude is larger than 5N. Therefore controlling the tension T4 using a single loop PID controller at T4ref=5N will cause the tension T4 to drop to 0N. This severely affects the lateral control system in span 4. Further the low tension spikes in the winding section-Span4- will lead to badly wound eccentric and wobbly web roll. This along with poor lateral accuracy of winding leads to practically unusable rolls. To avoid these problems the experiments were conducted with T4ref=10N-figure 3.2.7(a)-(e). Thus the tension spikes which propagate to span 4 never cause the tension T4 to go too close to 0N. But as can be seen in figure 3.2.9 the spikes in tension T4 are reduced considerably by the use of the proposed algorithm. The overall amplitude of the tension T4 is found to be less than 1N. Occasional spikes in tension do not appear to exceed 3 N. It is worth noting that the noise in tension measured using load cell and the measurement equipment is approximately 0.5 N in amplitude.

5.3. Active dancer based closed loop tension control

R2R system is operated at a speed of 0.04 m/s and a reference tension of 5N. Tension span-2 is controlled using the dancer system with fuzzy controller. The results are as shown in fig 3.3.8. It can be seen that the assumptions made during the design of control system is valid. The tension fluctuations never exceed amplitude of 1.25N. Also it can be seen that the position control is all that is needed for controlling the tension. Since there is sufficient tension in the span the slip of web at lateral error control system can be minimized, all the while maintaining a reasonably low tension. Thus this method is suitable for controlling web tension while printing functional material for printed electronics.

5.4. Slot die coating

Detailed results and discussions are presented in section 3.4.4. These may be summarized as follows:

- the resistance first decreased as tension was increased from 5 N and reached local minima at around 8 N.
- From 8 N onwards the resistance increased and reached local maxima at around 12 N and decreases till 20 N.

- When examining the standard deviation of resistance in Fig. 3.4.5(b), it can be seen that there are two local minima; one at 8 N and the other at 17.5N.
- Peak and valley like features are observed in SEM image of PEDOT: PSS coating.
- It can be stated that as peak features increase the resistance also increases and that peaks probably don't or contribute to a lesser extent to the conduction of electrons compared to the valleys.

6. Conclusions

Roll-to-roll system is a very complex system. If it can be harnessed for mass production of printed electronics, the whole electronics industry will be revolutionized. R2R although having been used for some low resolution printed electronics, still has plenty more to offer. To date gravure printing has been implemented with R2R system. If offset printing can be incorporated into it the resolution and complexity of electronic circuits that can be printed can be improved further. In this thesis several control systems have been developed for a variety of printed electronics printing applications. The key to success in printing electronics on the R2R system is to design the control system to suit the processing technique. One way to achieve the required control performance from an existing R2R system in a short development time is to use fuzzy logic. Also it is crucial to acknowledge the interaction taking place between the web spans. One disadvantage of using an industry built multi span R2R system is that it is built to control tension of each span independently. The interaction is ignored by following tension guidelines, which are misleading. In this work

6.1. Offsetprinting

Offset printing is a promising tool for mass production of precision printed electronics. But there are several obstacles to be overcome to implement it in a mass production system such as the roll-to-roll (R2R) system. In this work a new control system is designed to incorporate an offset printer into an R2R system. The printer has a discontinuous blanket and this introduces several disturbances into the R2R system. These have been overcome with the use of new control architecture and fuzzy logic based tension feed-back control system which avoids the use of dancer system. Statistical techniques along with experimental data were employed in the design of the new control system that considerably reduces the disturbances in the process span. Moreover the system was operated at a very low tension which is essential for printed electronics. Finally the system was used to print patterns in the form of fine silver mesh on PET substrate establishing the mass production capability of the system. The direct advantage of using the offset printing system in the continuous mode is that the production rate is nearly quadrupled, as four discrete steps are done simultaneously. This work will further facilitate registration control.

6.2. Reduction of interaction between spans using fuzzy logic

A new tension controller has been created for Roll-to-roll system that offers a tradeoff between commercial single loop tension control and more specific MIMO type tension controllers. It has been designed keeping in mind the printed electronics industry where very precise and low tensions are required. At the same time the frame work of the design is generic and can be applied to any roll to roll based system. The key contribution of the work is that it is model less approach to control and uses fuzzy logic to prevent propagation of tension disturbances from one span to another. This allows the system to be designed in an iterative fashion following a path similar to the design of a PI controller but with provision to take into account disturbances from previous span by fuzzy techniques and thereby decoupling the tension control of a span. This system has been tested in an R2R system integrated with an offset printer. The system considerably reduced the disturbances produced by the offset printer that propagated to the next tension span. An online self-tuning mechanism ensures that the system tunes itself according to the current nature of the system and prevents disturbance propagation. Besides being useful to printed electronics industry it will find application in converting industries where large numbers of tension spans are involved.

6.3. Active dancer based closed loop tension control

A fuzzy logic based tension control algorithm is developed for an active dancer system. An unconventional approach is presented, which does not use any model. This imparts flexibility to not just to tuning or calibration of dancer system, but also gives flexibility to dancer design. The algorithm will find application in R2R based printed electronics industry as the system is capable of operating at low tensions with only minute fluctuations. In future it also will find use in precise printing registration control.

6.4. Slot die coating

PEDOT:PSS is coated on PET substrate using slot die coating. During the coating process the flow rate of ink and web velocity were kept constant and the web tension alone was varied from 5N to 20 N in steps of 2.5 N. The resistance of the resulting coatings made at different tensions was measured and analyzed. The result indicated that the relation between resistance and tension was highly non-linear. Further the measured resistance varied about a mean for a given tension. This variation was studied by plotting the standard deviation of the resistance against the tension. Based on the resistance and standard deviation of resistance, the optimum tension was found to be 8 N. Examination of SEM images revealed that the surface of coating had clearly distinguishable peak and valley like features. Further the SEM images were analyzed using image processing techniques and it was established that peak like features played a significant role in the resistance of coating. It can be stated that tension change had altered the surface texture which in turn affected the resistance. Future work in this field will be directed at finding the cause of the effect that tension has on the surface of coating.

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