Markku Ohenoja

COMPUTATIONAL METHODS FOR EXPLOITING IMAGE-BASED DATA IN PAPER WEB PROFILE CONTROL
MARKKU OHENOJA

COMPUTATIONAL METHODS FOR EXPLOITING IMAGE-BASED DATA IN PAPER WEB PROFILE CONTROL

Academic dissertation to be presented with the assent of the Doctoral Training Committee of Technology and Natural Sciences of the University of Oulu for public defence in Kuusamonsali (YB210), Linnanmaa, on 16 September 2016, at 12 noon

UNIVERSITY OF OULU, OULU 2016
Ohenoja, Markku, Computational methods for exploiting image-based data in paper web profile control.
University of Oulu Graduate School; University of Oulu, Faculty of Technology
University of Oulu, P.O. Box 8000, FI-90014 University of Oulu, Finland

Abstract
Sheet and film forming processes such as paper manufacturing pose a challenging monitoring and control problem, where quality variations are classified into machine direction (MD), cross-machine direction (CD) and residual variation. The measurements are typically collected with a scanning sensor that covers only a small part of the paper web, and therefore provides a very limited view of the paper web, setting performance limitations on the online monitoring and control.

The development of cameras, light sources and computation hardware enable the consideration of utilizing in-use web inspection systems in paper machines to measure the paper web variations with a considerably higher resolution, sampling rate and coverage. The light transmittance images captured with this kind of system need, however, to be converted into a controllable quality property, such as basis weight, in order to utilize the new measurement information for control purposes.

In this thesis, computational methods are identified and developed that are capable of combining light transmittance and scanning measurements, and can efficiently utilize the combined information for control purposes. The possible benefits gained with these image-based measurements in paper machine online monitoring and profile control are evaluated in a simulation environment. In a real paper machine, the benefits are ultimately dependent on the machine configuration and the nature of paper variations therein.

It was found that with a suitable estimation method, light transmittance could increase the awareness of basis weight variations such as fast MD variation, tilted waves and dynamic CD variation patterns, which are practically undetectable using scanner-based measurement. The enhanced basis weight estimation enables a considerable improvement in the dynamic performance of profile controls. CD control was able to handle fast variations earlier classified as uncontrollable residual variation. In MD control, enhanced estimation enabled the development of a control strategy that led to improved reference tracking and disturbance rejection properties.

Keywords: control, estimation, imaging, measurements, papermaking, scanning, simulation
Ohenoja, Markku, Laskennallisia menetelmiä kuvapohjaisen datan hyödyntämiseen paperiradan profiilisäädössä. Oulun yliopiston tutkijakoulu; Oulun yliopisto, Teknillinen tiedekunta
*Acta Univ. Oul. C 577, 2016*
Oulun yliopisto, PL 8000, 90014 Oulun yliopisto

**Tiivistelmä**

Paperinvalmistus on yksi esimerkki levyjen tai kalvojen valmistusprosesseista, jotka ovat tyypillisesti haasteellisia prosessin monitoroinnin ja säädön kannalta. Laatuvaihtelut näissä prosesseissa luokitellaan koneensuuntaisiin (MD), poikkisuuntaisiin (CD) ja jäännösvaihteisiin. Paperikoneella mittaukset kerätään tavallisesti radan yli liikkuvalla skannaavalla sensorilla, joka tarjoaa vain hyvin rajoitetun määrän informaatiota paperiradasta, asettaen siten rajoituksia online monitoroinnin ja säädön suorituskyvylle.

Kameroiden ja valonlähteiden kehitys sekä laskentakapasiteetin kasvu mahdollistavat paperiradan vaihteluiden mittauksen huomattavasti paremmaksi korkeamman resoluutiolle ja näyteenottoväliillä jo käytössä olevilla viianlaisuighbourdelmilla. Vianlaisuighbourdelmän keräämä valon transmitanssitieto pitää kuitenkin muuntaa esimerkiksi nelioimassatiedoksi, jotta uutta mittausinformaatiota voitaisiin hyödyntää myös prosessin online säädössä nykyisillä toimialueilla.

Tässä työssä on identifioitu ja kehitetty laskennallisia menetelmiä, jotka kykenevät yhdistämään kuvantavan ja skannaavan mittauksen sekä käyttämään tätä yhdistettyä tietoa säätötarkoituksissa. Kuvapohjaisen mittauksen mahdollisia hyötyjä online monitoroinnissa ja profiilien säädössä on arvioitu simulointiympäristössä. Saavutettavat hyödyt paperikoneella ovat lopulta riippuvaisia myös koneen konfiguraatiosta ja koneella ilmenevien laatuvaikuteluiden luonteesta.

Tulokset osoittavat, että transmittanssimittauksen ja tehokkaan estimointimenetelmän avulla kyetään lisäämään tietämystä nelioimassatiedoksista, joita ei käytännössä voida havaita pelkän skannaavan mittauksen avulla. Estimoinnin parempi suorituskyky mahdollistaa myös profiilisäätöjen dynamisen suorituskyvyn kasvattamisen. CD-säätiö voitiin laajentaa kattamaan myös nopeita vaihteluita, jotka ovat aiemmin luokiteltu jäännösvaihteluiksi. MD-säädelle voitiin kehitää säätöstrategia, jonka avulla sekä asetusarvojen seurantaa että häiriöiden vaimennusta pystyttiin parantamaan.

**Asiasanat:** estimointi, kuvantava, mittaus, paperinvalmistus, simulointi, skannaava, säätö
Acknowledgements

This research was carried out at the Control Engineering Research Group at the University of Oulu, during the years 2009–2015. The work was initialized in two research projects, EffTech and EffNet, which were coordinated by the Finnish Bioeconomy Cluster Oy (earlier the Finnish Forestcluster Oy). The research was mainly funded by the International Doctoral Programme in Bioproducts Technology (PaPSaT). Walter Ahlström Foundation, Tauno Tönning Foundation, Automaatiosäätiö, and Riitta and Jorma J. Takanen Foundation are also gratefully thanked for their financial support.

I wish to express my gratitude to Professor Kauko Leiviskä, who gave me an opportunity to combine two highly interesting topics; automation engineering and paper manufacturing. I also appreciate the guidance and the patience of my supervisor during this work. The staff at the Control Engineering earn a special recognition due to their cooperation, problem solving whenever needed, and the great working atmosphere they create every day. Johanna Ylisaari and Ari Isokangas are thanked for their valuable effort in sorting out and developing the simulator at the beginning of this work. I also thank the reviewers, the research partners, and the PaPSaT board and members for their helpful comments during the way.

Finally, I want to thank my family: My parents, Anja and Jukka, thank you for your life-long support and encouragement. Thank you Katja, for being the most important one, sharing all this and showing me the way. My sons, Oskari and Arttu, thank you for bringing so much happiness and laughter to this world.

Oulu, May 2016

Markku Ohenoja
List of original publications

This thesis is based on the following publications, which are referred throughout the text by their Roman numerals:


The author was the main contributor in Publications II–V. Kauko Leiviskä had the supervisor’s role in these publications. In Publication I, the author was responsible for developing one of the estimation methods for the described problem and performing the experimental studies with that method. Johanna Ylisaari conducted the development and experiments with another estimation method and participated in the writing process. Kauko Leiviskä and Risto Ritala acted as supervisors in Publication I.
Table of contents

Abstract
Tiivistelmä
Acknowledgements 7
List of original publications 9
Table of contents 11
1 Introduction 13
  1.1 Background ................................................................. 13
  1.2 Objective and scope .................................................... 15
  1.3 Research process and dissertation structure .................... 17
2 Literature review 19
  2.1 Sensor arrangements in a paper machine ....................... 19
     2.1.1 Scanning sensor .................................................. 19
     2.1.2 Multiple sensors ................................................ 20
     2.1.3 Web-wide measurements .................................... 21
  2.2 Online profile control ................................................. 22
     2.2.1 MD control ......................................................... 22
     2.2.2 CD control ........................................................ 24
     2.2.3 Model identification .......................................... 29
3 Results 31
  3.1 Estimation ................................................................. 31
  3.2 Control ....................................................................... 33
     3.2.1 CD control ......................................................... 34
     3.2.2 MD control ........................................................ 36
  3.3 Generalization .......................................................... 40
4 Discussion 45
5 Conclusions 49
References 51
Original publications 59
1 Introduction

1.1 Background

Among industrial processes, two-dimensional web processes (also known as sheet and film forming processes) pose a particularly challenging problem with respect to process monitoring and control. These processes cover for instance polymer film extrusion, many types of coating processes, sheet metal rolling, plate glass manufacturing and, of course, paper manufacturing. The common control objective of these processes is to simultaneously manage quality variations both along and across the production line. Effective control is reflected in improved product quality and production rate, reduced usage of materials, elimination of product rejects, and reduced energy usage (VanAntwerp et al. 2007). From the end users’ point of view, a more uniform paper product leads to improved runnability in pressrooms (Bialkowski 1990).

In paper manufacturing, the paper web is formed by distributing a low consistency fiber suspension on the forming belt, which guides the product through several processing stages where water is removed and the surface properties are adjusted before reeling up. Modern paper machines have a production speed of up to 40 meters per second with a web width of over 10 meters (Ritala 2009). The most important quality properties controlled online are basis weight, moisture content, and thickness, or caliper. The web variations are broken down into machine direction (MD), cross-machine direction (CD), and residual variation (Cutshall 1990). MD variation occurs in the whole sheet as a function of sheet length, or time. The MD profile describes the variation in the average value of the property within the produced paper reel. CD variation reflects the zero-mean CD profile that is assumed to be stable with time. The importance of a uniform CD profile comes from the fact that the produced paper reel is ultimately cut to narrower customer reels. High variation in CD leads to customer reels with varying quality. Residual, or random variation is the total variation with MD and CD components subtracted. The variation components are illustrated in Fig. 1.

Separate control systems exists for MD and CD variations in a paper machine. The CD process forms a large-scale, challenging multi-input-multi-output (MIMO) control problem with an uneven number of inputs and outputs and many constraints. CD control has been extensively studied and numerous possible control algorithms, also focusing on computational challenges, model uncertainties and robustness.
issues, have been proposed in the literature (see Chapter 2.2.2). The MD process constitutes a rather traditional control problem with interactions and can therefore be handled using proportional-integral-derivative (PID) controllers or model predictive control (MPC). The goal of the measurement system is to provide MD and CD estimates for control purposes and to monitor the residual variation for diagnostic purposes (Ritala 2009). Usually, measurements are collected with a scanning sensor, which is not an optimal solution as it sets many difficulties and performance limitations for online control, see Spitz (1990), Kjaer et al. (1995).

![Fig. 1. The variation components of a two-dimensional web (Paper II, published by permission of NPPRJ).](image)

It is known that the web-wide measurements would enhance the estimation and the control performance if feasible measurements were available (Tyler & Morari 1995). Therefore, optional web-wide measurement systems (Francis 1991, Williams et al. 1996, Heaven et al. 2000) have been developed for paper machines, but without a complete success due to their high expense and calibration difficulties (Raunio et al. 2013). More recently, the decreased price and increased speed and performance of cameras and light sources, as well as the increased computational capacity, allow the utilization of in-use technology in paper machines to capture high-resolution light transmittance images of the whole web. The applicability of a web inspection system (WIS) for these purposes is studied in Raunio (2014), where images were processed and used in the creping pattern characterization of tissue paper and in estimation of small scale paper structure, shrinkage and basis weight of newsprint paper. Image pre-processing is required for removing overlapping areas from images and correcting disturbing elements such as the movement and vibration of the paper web, variation in illumination intensity and geometric distortions (Raunio 2014).
1.2 Objective and scope

This thesis concerns the utilization of web-wide, image-based measurement, such as light transmittance measurement, in paper machine online monitoring, CD control, and MD control. The system performance is evaluated as a combination of the quality of image-based measurement and control based on the measurement. The reference is scanner-based measurement and control. The two measurement principles are illustrated in Fig. 2.

![Diagram of scanning measurement (left) and imaging measurement (right) of the paper web (Paper II, published by permission of NPPRJ).]

Light transmittance measurement has obvious benefits: the resolution with this kind of measurement can be very high as WIS images are captured at approximately 330 images per second with a sub-millimeter resolution (Raunio et al. 2013), whereas, with scanning measurement, only a very small part of the paper web, as little as 0.001%, is actually measured (Kjaer et al. 1997). In addition, some of the problems encountered due to the movement of the traversing scanner can be overcome with web-wide measurements. This opens up new possibilities for detecting and classifying variations. Light transmittance is a visual measure of paper quality and the measurement is therefore useful in monitoring and troubleshooting. Light transmittance is sensitive to several paper properties, such as basis weight, moisture (water content), and filler content. Therefore, for control purposes, the transmittance images need to be converted into a meaningful, controllable property and any possible improvements in control performance are dependent on how well this calibration can be realized. The calibration naturally involves utilizing scanner-based measurement. The new, combined measurement information, referred to here as image-based measurement, along with the improved sampling rate, may require the reconsideration of the control algorithms that are computationally feasible for use with such data.
The research problem can be formulated into the following research questions:

- What new information may be provided by light transmittance measurement and can it be converted into image-based basis weight measurement for monitoring and control purposes?
- How could the profile control strategies be developed in order to use image-based measurement effectively and how are the benefits seen in different variation components and dynamic control performance indices?
- Can the methods be generalized for more complex cases, either with decreased light transmittance measurement quality or increased size of the control problem?

The aim of this study is therefore to identify and develop computational methods that are capable of combining measurements and can efficiently utilize the new measurement information for control purposes, in order to evaluate the possible benefits gained with image-based measurement in paper machine online monitoring and profile control. The study aims to demonstrate the feasibility of the proposed computational algorithms for the research problem through the results. A further aim is to illustrate the estimation and control performance based both on image-based measurement and scanner-based measurement. The evaluation of the results should show to what extent paper machine operation could benefit from image-based measurement and under which circumstances these benefits in monitoring and control performance would be achievable.

The research work is documented in five original articles. The two conference articles (Paper I and Paper III) present the computational algorithms adopted for this problem. Paper II and Paper IV mainly focus on evaluating the estimation and control performance and the potential benefits gained with image-based measurement. Finally, Paper V presents the control algorithm extended to a larger control problem. Fig. 3 illustrates how the original articles are related to the subject matter and the core of this thesis.
In this thesis, the performance of the computational algorithms is examined in a simulation environment. The simulation offers a tool for gaining information that would be impractical to obtain during the normal operation of the process or when the test arrangements would not be economically feasible. The computational methods for paper machine online estimation and control purposes are mainly tested with a simulator that mimics the online operation of the measurements, profile estimation, and control actions. It is assumed that the challenges related to the data acquisition, storing, and processing of the light transmittance measurement captured with WIS technology have been solved and the transmittance measurement can be down-sampled to a spatial resolution of 1 cm and temporal resolution of 1 s. It is further assumed that the scanning measurements can be captured with the same spatial resolution, and the two measurements can be aligned. The simulations consider newsprint quality paper and consistency profiling actuators for CD control. The light transmittance measurement is formed as a linear combination of three paper properties. The paper properties are mainly simulated as deterministic variations.

1.3 Research process and dissertation structure

The research work was conducted between 2009 and 2015, initially started in the research programs Efftech (2008–2010) and EffNet (2010–2013) by the Finnish Forestcluster Ltd. (later the Finnish Bioeconomy Cluster, FIBIC Ltd.). During these projects, suitable estimation and control algorithms were screened and applied for
use with image-based measurement. In this thesis, the calibration and estimation problem of image-based measurements is mainly solved with the method *Dynamic validation of the transmittance* developed at Tampere University of Technology (Ihalainen *et al.* 2006). Scanner-based measurements are treated in CD with an *exponential moving average filter*. The CD control is developed based on a *steady-state linear quadratic controller* coupled with a temporal *internal model controller* (Chen 1997, Chen 1999). The original CD controller was extended to handle multiple CD profiles and actuator sets in this thesis. The CD control structure was chosen over MPC due to its considerably smaller computational requirements, therefore being able to handle profile information updating more frequently than with scanner-based measurement. MD control utilizes *proportional-integral (PI) control and the Smith predictor or internal model control (IMC)* and the control strategy has also been extended in this thesis to utilize a secondary input in *CD-assisted MD control*. The response model identification is based on *bump tests* and the *prediction error minimization algorithm* in Matlab®.

The paper machine simulator utilized was originally designed at Tampere University of Technology (Ylisäari *et al.* 2009). During the above-mentioned projects, the simulator was refined by adding transmittance measurements, estimation algorithms and control algorithms in collaboration with the research partners. Matlab® was used for coding the simulator and performing the simulations in this thesis.

The layout of this thesis is as follows: Chapter 1 gives a short introduction to the topic and the aim of this thesis. Chapter 2 presents a literature review of possible sensor arrangements and online profile control algorithms applied to paper machines. Issues related to process model identification are also reviewed. In Chapter 3, the results related to the three research questions are presented, with each research question dealt with in a separate subsection. Discussion based on the results and the research problem is given in Chapter 4. Chapter 5 summarizes the findings of this thesis.
2 Literature review

The performance of the online control system in a paper machine is dependent on numerous factors such as the online measurements system and sensor arrangements, filtering techniques and other data processing, sheet wandering and shrinkage, interactions between the properties and across the paper web, and numerical issues and constraints in control calculations. Naturally, not even the most sophisticated control design can overcome the sloppy design of the equipment or the restrictions set by the other components.

2.1 Sensor arrangements in a paper machine

2.1.1 Scanning sensor

The very first paper machine gauges in the 1950s were installed in a fixed position and could therefore reflect only MD variations (Wang et al. 1993b). Scanning sensors were introduced in the paper machine in the 1960s. Initially, the scanning, or traversing weight and moisture gauges, provided valuable information mainly for troubleshooting, but also revealed the ugly truth of CD variations (Cutshall 1991). Despite the well-known limitations that scanning measurement imposed on profile controls (see e.g. Spitz (1990)), scanning sensors are still used as the main measurement principle for profile estimation and control.

The sensor is mounted in a frame above the production line and the sensor travels back and forth across the paper web. While the paper web moves quickly in the machine direction, the measurement path forms a zigzag pattern, as illustrated in Fig. 4. Thus, the measurement data contains mixed information about both CD and MD variations. The ultimate problem related to the scanning sensor is MD/CD separation. MD variations may be aliased into the CD profile estimates due to the periodic nature of the variations and the sensor movement. The MD/CD interactions and 2D aliasing are treated in e.g. Shakespeare (2001), Skelton et al. (2003).

The traditional method for MD/CD separation is the exponential moving average filter, first applied to this problem by E.B. Dahlin, see Mäenpää (2006). This method has well-known limitations, but is easy to implement for any profile estimation problem. Another well-known solution for profile estimation is the observer-based method, relying on the recursive least squares algorithm for CD
estimation and extended Kalman filter to estimate the MD dynamics (Wang et al. 1993b). Both methods assume that CD profile changes are considerably slower than MD variations and the latter method also requires a careful tuning of the algorithms. More observer-based methods are presented in for example Bergh & MacGregor (1987), Tyler & Morari (1995). In Skelton et al. (2003) and Duncan & Wellstead (2004), scanning was treated as a one-dimensional sample of a two-dimensional process and reconstruction of the 2D variations was based on the generalized sampling theorem. More information about the application of the 2D systems theory in paper manufacturing can be found in Wellstead et al. (1997), Wellstead et al. (2000) and the references therein. Also self-tuning, or adaptive model-based methods relying on rational polynomials, spectral analysis, principal component analysis, and wavelets have been suggested (Kristinsson & Dumont 1996, Heath 1996, Rigopoulos et al. 1997, Chen 1997, Nesic et al. 1997), but their implementation would be more straightforward with web-wide measurement.

One recent development to the scanning sensor is the possibility to control the movement of the sensor (Nuyan & Sorsa 2008). The scanning speed and location can be adjusted to suit the control situation and the process state, so that the scanning takes place where faster measurements and better estimates are required. A sensor path of this kind of adaptive scanning system is illustrated in Fig. 4.

![Fig. 4. Sensor arrangements in a paper machine.](image)

### 2.1.2 Multiple sensors

The MD/CD separation problem may be tackled by increasing the number of sensors. In Duncan & Taylor (2007), the observer-based method utilizing a scanning sensor and an additional fixed position sensor was presented. The fixed
sensor would allow the removal of MD variation from the scanning measurement, thus enabling more reliable CD estimation. Another multiple sensor approach has been proposed in Begemann & Münch (2001), where the additional sensor can either be in a fixed position or a scanning sensor.

The potential multiple scanning sensor arrangements for sheet-forming processes were evaluated by Chang et al. (2001). They used an image-based approach to design and evaluate the sensor trajectories that produce the smallest averaged standard deviation over the spatial locations. The best coverage can be achieved with multiple sensors travelling in the same direction, but a sub-optimal solution of multiple sensors with full sweeps and different directions is more practical due to the decreased number of turns, accelerations and decelerations of the sensors. These two sensor arrangements are also illustrated in Fig. 4.

2.1.3 Web-wide measurements

Besides the problem of MD/CD separation, the scanning sensor in fact measures only a very small part of the paper surface, as little as 0.001% (Kjaer et al. 1997). Therefore applying web-wide measurement would both solve the aliasing problems and substantially increase the information content on the paper web variations. The effects of the scanning and stationary sensor arrangements on estimation and control performance have been compared in Tyler & Morari (1995). There have been numerous attempts to implement web-wide measurement and they have been mostly reported in conference proceedings and patents.

The early attempts of web-wide measurements utilized optical measurement for the estimation of color, brightness and opacity (MacTaggart 1986), and paper weight (Francis et al. 1989, Francis 1991). The latter aimed to align the sensors downstream to CD actuators and use the scanning sensor for the calibration. Fischer et al. (1990) used radio wave techniques for water content measurement in a sensor array.

In the late 1990s, full sheet imaging systems were introduced and they have been reported for example in Williams et al. (1996), Ferguson (1997), Chen et al. (1998) and Chen (1999). The method relies on raster scanning of light transmission or reflection. The system uses near infrared (NIR) wavelengths and Tungsten lamps. In Heaven et al. (2000) and Hu et al. (1998), basis weight estimations were based on multi-point water weight foil sensors in a Fourdrinier paper machine. By providing measurements already at the wet end, the transport delay is substantially decreased. In addition, methods based on the detection of the dry-line in a
Fourdrinier wire have been proposed (Niemi & Backstrom 1994, Kjaer et al. 1997, Larsson et al. 1998).

The main challenges in most web-wide measurements, relying on visible and near-visible bands, are related to the conversion of the measurement information into some controllable quality property, sensitivity to the measurement conditions and the sheet composition, and disturbances arising between the different measurement positions (Shakespeare 2001). Although there have been numerous attempts to provide web-wide measurements in the industry, it has not been found to be feasible. There is, however, one exception: the web inspection system.

The modern web inspection systems were developed in the 1990s (see e.g. Masters et al. (1997)) and rely on detecting the changes in pixels recorded with camera-based devices. These changes can be related to many typical faults in the paper web. By processing only the abnormal phenomena, the computational burden was kept at an acceptable level. The recent development of cameras, light sources, and increased computational capacity have enabled high-resolution online imaging with the same arrangement (Ihalainen et al. 2012, Raunio 2014). Current systems utilize CCD cameras and LED lights. The correlations between light transmittance and basis weight variations in newsprint grade have been reported in (Raunio 2014), as well as the application of utilizing light transmittance in shrinkage profile estimation and creping pattern characterization. Similar techniques have also been utilized in troubleshooting installations for board grades (Söderberg et al. 2010).

2.2 Online profile control

2.2.1 MD control

MD control of the main quality properties is quite straightforward in comparison to CD control. The dynamics of the actuator responses are usually described with the first-order transfer function and dead time. Hence, the problem may be even solved with a simple PI or PID controller. Linear stochastic models in MD control have been discussed in an earlier review by Brewster & Bjerring (1970). However, the interactions between different quality properties and the white water system can efficiently be taken into account with multivariate model predictive control.

Most of the variations in MD can be attributed to disturbances and pulsations occurring prior to the headbox (Wang et al. 1993a). For example, fluctuations in consistency, fines content, and dissolved solids cause variations in first-pass
retention and basis weight (Orcocotoma et al. 2001). In Shakespeare (2001), some of the root causes for MD variations are mentioned: for example, poorly maintained process equipment, improper tuning of control loops, suboptimal dimensioning of machine services, variation in headbox pressure, reciprocating devices on the machine such as doctor blades and cleaning showers, and non-uniform wearing of the wire during operation. MD variations occur on very different time scales, from formation changes in milliseconds to long-term variations with periods longer than 200 seconds (Cutshall 1990).

The most important MD properties under online control are basis weight, filler content, moisture, and white water consistency, where the latter has an indirect effect on paper formation and surface properties. Basis weight is controlled using the thick stock valve by adjusting the amount of pulp flowing into the headbox. Filler content and white water consistency are adjusted with the dosage of the filler and retention aid to the short circulation, respectively. The steam pressure of the drying cylinders is used for controlling moisture. (Ritala 2009)

The performance of seven different control strategies focusing on basis weight and filler content have been compared in Hagberg & Isaksson (1995) and Isaksson et al. (1995). The control strategies were based on Smith predictor control, \( H_\infty \) loop shaping, dynamic matrix control (DMC), and generalized predictive control (GPC). The MD control problem was found to be a compromise between nominal performance and robustness, as well as a compromise between the set point following and regulatory control. Performance evaluations can also be found in Makkonen et al. (1995) and Fu & Dumont (1995).

The most traditional way to control MD variation is the Smith predictor and its discrete time version, the Dahlin controller. The Smith predictor includes an internal model of the process with and without the dead time, in addition to some controller structure. Usually, a PI or a PID controller is used with a low-order model. A modification of the Smith predictor presented in Makkonen et al. (1995) makes it possible to vary the control signal between samples. It also computes output predictions in the inter-sample region while the true process output is used as a correction signal. Hence, the controller can be tuned for the process with no delay. A similar control structure was also introduced in Baki et al. (2001). They pointed out the need for more robust tuning algorithms for basis weight control and implemented a PID controller with derivative filtering in a pilot paper machine.

Early model predictive control approaches can be found in Wang et al. (1993a), Makkonen et al. (1995) and Fu & Dumont (1995). In Wang et al. (1993a), the authors aimed to improve the dynamic bandwidth of the basis weight MD control.
by relying on adaptive process model identification and GPC. The GPC controller calculates the predicted control increments over a certain horizon, but updates only the next control action (receding horizon principle). If the minimum variance predictions through the prediction horizon are used, then the optimization criterion is a linear quadratic function.

Current MPC approaches enable the simultaneous control of the main properties and taking into account the interactions between the different MD control loops. The control actions are optimized with respect to a joint goal of all the loops, possible constraints, and future behavior of the process predicted on the basis of the process models. The challenge comes from the selection of the time horizons and the weightings between the individual goals and penalties; the modern control theory utilizes $H_2/H_\infty$ norms, whereas control engineers are more accustomed to evaluating indices such as overshoots and settling times. Tuning issues are discussed e.g. in Shi et al. (2015). The effect of a possible model-plant mismatch in MD-MPC has been studied recently in Yousefi et al. (2015). Hauge et al. (2005) have demonstrated the effectiveness of using a mechanistic non-linear model in MD-MPC, enabling easy adoption of the model and the controller in new production plants and operating points. Multivariable MPC for MD control has been reported e.g. in Chu et al. (2011). Also, offline MPC for grade change situations that gives the manipulated variable trajectories for online MD control is discussed in Chu et al. (2011).

The MD control performance can be improved through the coordinated control of both MD and CD actuators. For example, Bergh & MacGregor (1987) presented the linear quadratic Gaussian control approach jointly controlling MD and CD variations. They showed how short-term MD variations were reduced using CD actuators, also contributing to MD regulation. In Hall (1991), the utilization of CD actuators to speed up the MD moisture response was proposed.

### 2.2.2 CD control

CD control is a very challenging task; it forms a high dimensional, spatially distributed problem with hundreds or even thousands of inputs and outputs, where the number of measurement positions exceeds the number of actuator positions. The CD actuator response is wider than the actuator itself; hence the response also affects the adjacent actuator zones. There are also interactions between different control loops as one actuator set may affect more than one quality property. Naturally, the actuator movements may be constrained. Additionally, there are
challenges set by the sensor arrangements, sheet wander, and shrinkage, which are seen as inaccurate response models. Therefore, only sub-optimal control actions are possible and usually the control target is to minimize the deviation of the sheet properties in the CD while satisfying the constraints, tolerating any possible plant-model mismatch, and being computationally efficient.

Process variation in the CD often takes a sinusoidal shape, especially in heavier grades (Adler & Marcotte 1994). The CD variations are sourced from the headbox, where the flow is changed from a round pipe to a web-wide flow. Initially, the flow variation due to design and cleanliness is seen in the basis weight and fiber orientation, and it is propagated to moisture, caliper, and density variations. Further CD variation is caused by downstream processing and deficiencies. (Cutshall 1990) Some MD operating conditions, such as the headbox consistency level, slice opening, stream valve control and pulp pH have some impact on CD profiles. Additionally, the junctions between the deckle boards and the headbox are not smooth, causing turbulence. (Adler & Marcotte 1994) It is commonly assumed that fluctuations in the CD occur on a much slower time scale than those in the MD. This is also the justification for why the dynamic restrictions of the scanner measurement are not considered to be crucial. However, Cutshall (1990) presented that time-dependent CD variation does exist between consecutive reels. On the other hand, Bergh & MacGregor (1987) mentioned that redesigning the process would be more appropriate than utilizing more advanced control, if rapid CD profile changes occur.

CD control is needed for basis weight, moisture, thickness, and coating profile adjustments. Basis weight is traditionally adjusted with slice screws, shaping the slice lip opening of the headbox. Modern paper machines may also rely on dilution valves that affect the consistency profile of the jet flow. For moisture profiling, there are usually two actuator sets: zone-structured steam boxes and re-moisturizing showers. The thickness profile is adjusted with steam-heated, zone-structured rolls and the coating weight profile is adjusted with a bending blade. (Ritala 2009)

Despite the controllable property in question, a CD model is typically formed as follows: the CD process, i.e. the actuator input-output relationship, is described with a fixed, approximate non-square interaction matrix model, usually assuming identical and equally spaced actuators. It is further assumed that the response is separable and, therefore, the dynamic response of the CD actuator set can be described with a scalar first-order plus delay model. For the different actuator sets, the width of the actuators differ and their spatial responses are very different. The
dynamic responses of the actuator sets vary significantly and are dependent on the machine speed and the distance between the actuating and measurement locations. Depending on the control design, some further assumptions might be needed or on the contrary, some of the above-mentioned assumptions may not be required. The control methods presented in the literature are often based on linear quadratic control or model predictive control.

Rigorous constrained linear control methods such as quadratic programming (QP) were proposed for CD control problem as early as the 1970s (see e.g. Boyle (1977)). The early CD control systems were, however, limited by the hardware and software constraints and the QP methods were impractical. Therefore, the control was based on limited resolutions and simplified control strategies, such as the inverted interaction matrix approach (see e.g. Wilkinson & Hering (1983)), where the number of data boxes was matched to the number of actuators and only steady-state behavior was accounted for. Pseudo-inverse could be used for a non-square interaction matrix. Approaches relying on linear algebraic models and quadratic performance index were refined later in Chen & Wilhelm (1986) and Bergh & MacGregor (1987). In the former paper, the optimal control solution with QP and the sub-optimal, but computationally feasible, solution with the quadratic penalty function (QPF) were evaluated. In the latter study, a general solution of simultaneously controlling both the CD and the MD changes in sheet-forming processes, based on linear quadratic Gaussian (LQG) control was presented. Hence, they also accounted for the dynamic behavior of the process and modeled the disturbances as a multivariate time series. In the 1990s, the CD controllers applied were able to handle finer resolution profile data and coordinate between the actuator sets by spatial frequency separation. The control algorithm presented in Heaven et al. (1994) was based on linear quadratic steady-state optimization and PI control. The CD dynamics were accounted for in later studies by Duncan & Bryant (1994), Tyler & Morari (1995), Chen (1997) and Corscadden & Duncan (2000).

In general, linear control cannot take constraints into account very effectively, since it can only penalize the control action in the objective function. Anti-windup controllers may be used to modify the linear control system. The traditional anti-windup methods, relying on clipping or scaling the inputs, may lead to decreased closed-loop performance (VanAntwerp et al. 2007). Linear control has been proposed with anti-windup compensation methods for the CD control problem, e.g. in Kristinsson & Dumont (1996), VanAntwerp et al. (2001), Rojas et al. (2002a), Rojas et al. (2002b), Heath & Wills (2004) and Morales & Heath (2011). The
benefit of the linear control techniques is the lower computational effort required in comparison to MPC and other receding horizon techniques.

Model predictive control is an intriguing option for the CD process as it can explicitly handle the MIMO properties of the system, as well as the possible constraints. However, its computational load needs to be significantly reduced in CD control due to the high dimensionality of the problem, which makes it impossible to perform the calculations within the sampling interval. Basis functions allow this problem to be reconsidered with the possibility of satisfying all the requirements of CD control: good dynamic behavior, satisfaction of input constraints and parsimonious representation (Heath 1996).

Numerous different basis function representations have been proposed for CD control, including spline functions (Halousková et al. 1993), Gram polynomials (Kristinsson & Dumont 1996), Chebyshev coefficients (Heath 1996), Fourier transforms (Duncan & Bryant 1997), principal components (Rigopoulos & Arkun 1996, Rigopoulos & Arkun 2003) and wavelets (Ghofraniha et al. 1997, Chen 1997, Nesić et al. 1997, Zhi-huan et al. 1999). In addition, singular value decomposition (SVD) (Stewart et al. 2003) and pseudo-SVD (VanAntwerp et al. 2001) have been used for the interaction matrix, aiming to solve the numerical and robustness issues related to the CD problem. These representations reduce the size of the CD model significantly, e.g., in Zhi-huan et al. (1999), the original problem with dimensions of 420x88 was reduced to 53x22. In Heath (1996), a system with dimensions of 500x70 was described with 40 Chebyshev coefficients. Representation with orthogonal polynomials provides accuracy and smoothness for either the responses near the center of the sheet or those near the edge, but not both (Shakespeare 2001). The computational time can alternatively be reduced by using quadratic programming and a linear programming solver for the MPC problem.

Optimization can be performed by means of linear programming (LP) or quadratic programming (QP). LP provides a solution to the 1-norm or ∞-norm minimization problem while in QP, the problem is to minimize the variance of the sheet profile (VanAntwerp et al. 2007). For a more detailed description of these solution methods, see Saffer & Doyle (2004) and Bartlett et al. (2002), respectively. Solution methods based on the elliptic approximation of a quadratic MPC problem were presented in VanAntwerp & Braatz (2000a) and VanAntwerp & Braatz (2000b). Additionally, the computational time of the QP solvers can be decreased significantly by using so-called ‘hot starts’, i.e., utilizing the previous optimum as an initial point for the optimization (Rigopoulos & Arkun 2003).
The more sophisticated control design methods also address the robustness issues of CD control. Duncan & Bryant (1997) showed that the CD system can be decomposed into controllable and uncontrollable frequencies (the spatial bandwidth). Basis function expansions could therefore reduce the sensitivity of the closed-loop system to uncertainties in the interaction matrix if the control is designed only to operate in the controllable modes. Robust control for a CD system can be designed using so-called ‘squaring-up’ procedures. For example, Stewart et al. (2003) presented spatial loop-shaping tools for $H_\infty$, $H_\alpha$, and $\mu$-optimal CD control. Robust optimal control with an arbitrary non-square matrix was proposed in VanAntwerp et al. (2001). More recently, Morales & Heath (2011) presented a robust IMC-based controller that handles the constraints explicitly. According to Adegbege & Heath (2011), the robust MPC design not only increases the computational time, but may also result in a very conservative solution.

Yet another approach to profile control is two-dimensional control. Duncan et al. (2000) have examined the validity of the assumption of the separation between the dynamic response and the spatial response. They pointed out that the assumption might not hold true when the dynamic bandwidth of the system increases. This kind of increase is achievable by improving the speed of the actuators and measurement resolution. As a result, it may be necessary to design control algorithms that do not require the separation assumption or can accommodate deviations from the separable dynamics. One suitable approach may be to use techniques based upon the two-dimensional polynomial methods developed for optimal control (Heath & Wellstead 1995a, Heath & Wellstead 1995b) and it has been discussed in sheet-forming applications on a theoretical level, e.g. in Wellstead et al. (1997), Wellstead et al. (2000) and Duncan (2001). Additionally, the adaptive methods for simultaneous MD and CD control presented in Bergh & MacGregor (1987) and Rigopoulos & Arkun (1996) do not require the separation of the spatial and temporal direction.

The interactions between different properties and actuators have also been considered in CD control. The early methods use feedforward compensation (Hall 1991) or frequency separation (Heaven et al. 1994) to prevent competing control actions. MPC can handle interacting actuators either as measurable disturbances (Backström et al. 2001) or the problem of multiple properties and actuators can be solved simultaneously (Haznedar & Arkun 2002, Backstrom & He 2004, Fan 2003, Fu et al. 2006, Lahouaoua & Gheorghe 2010). Optimal controller approaches for multiple profiles and actuator sets have been presented in Shakespeare et al. (2003), Duncan & Heath (2008) and Duncan & Heath (2010).
2.2.3 Model identification

Process model identification is a crucial step in control system design. In paper manufacturing, and especially in the CD, the task is very challenging due to the limitations of the scanning sensor and the following reasons listed in Farahmand et al. (2009):

- geometric alignment of the CD actuators and measurement devices
- position of the individual actuator within the array
- wandering of the paper web
- paper shrinkage through the drying process
- flow pattern of the extracted liquid paper stock in the wire

In conventional CD control systems, mapping is used to correctly align the actuator zones with the measurement zones. This may cause some loss in profile resolution or poor controller performance. Misalignment of a few centimeters may result in sawtooth profiles, or actuator picketing, since actuators are adjusted to compensate for errors outside their control zone (Kristinsson & Dumont 1996). The widely accepted mis-map threshold of one third of the spacing between CD actuators can be exceeded only at the expense of the spatial bandwidth and the dynamic response of the control system (Taylor & Duncan 2006), i.e., the tuning of the control affects the mis-mapping stability. Also, the width of the CD response has an effect on the mis-map threshold. For narrow actuators, even small changes in alignment would lead to instability. However, these small mapping errors may be hidden by the small signal to noise ratio. (Gopaluni et al. 2008)

Traditionally, actuator response models are identified from bump tests by stepping several actuators in isolated CD locations in an open loop, see e.g. Kjaer et al. (1995), Heath (1996) and Gorinevsky & Gheorghe (2003). Bump tests are also a natural choice for MD model identification (Chu et al. 2011). The information content of the bump tests can be increased with more careful experimental designs (Featherstone & Braatz 1998). Another solution is to identify the models with pseudo-random probing sequences (Chen & Subbarayan 2002). This method is able to identify individual responses for each CD actuator, including both the spatial and the dynamic component. The spatial response can also be identified by the parameterization of a single actuator move, see e.g. Adler & Marcotte (1994) and Ghofraniha et al. (1997). The response of the slice lip can be examined more precisely by modelling the actuator bending with a full dynamic partial differential equation (Duncan et al. 2000). The model concerns the forces
applied to each screw in the slice lip and the positions of the screws. The results in Duncan et al. (2000) show that the assumption of separate dynamic and spatial components is valid in most cases. Another first principle model and its simplification are presented in Ghofraniha et al. (1995). The partial differential equation (PDE) approach is, however, not convenient for control purposes, which is why PDEs are approximated using the interaction matrix approach. Another approach is to discretize PDEs to give a 2D polynomial transfer function description. (Wellstead et al. 2000)

Shrinkage occurs in the dryer section and varies across the web, reaching maximum values at the edges. It is usually necessary to update the mapping function since shrinkage varies both with time and process state. This can be done with mini-bump tests, which do not affect the quality (the amplitude is approximately equal to the standard deviation) and using statistical analysis methods or fuzzy logic. (Adamy 1997) Misalignment due to shrinkage is magnified in faster machines. Many shrinkage models assume that the shrinkage phenomenon occurs symmetrically, which is not the case (Farahmand et al. 2009). Whilst updating the actuator response model is rarely necessary, updating the alignment needs to be done more often (Gopaluni et al. 2008). Hence, current approaches try to detect the mapping directly from the closed-loop data instead of using a model determined during open-loop bump tests. Closed-loop, or non-intrusive identification algorithms have been presented in Doyle & Saffer (2002), Farahmand et al. (2007), Stewart (2007), Gopaluni et al. (2008), Farahmand et al. (2009) and Ammar & Dumont (2013).

Actual shrinkage can also be measured. The forming fabric leaves periodic imprints on the paper which can be recorded either by measuring the intensity of the light transmitted through the paper using a CCD camera (I’Anson et al. 2008, Raunio 2014) or alternatively by measuring the amount of fluorescent light from the paper (Kaestner & Nilsson 2003). The image coming from the CCD camera or the time series coming from the fluorescence sensor is then examined in the frequency spectrum to detect the wire marks. Once the location of these marks is known, the shrinkage profile can be calculated.
3 Results

This chapter summarizes the most important research contributions published in the original articles.

3.1 Estimation

As presented in Chapter 1.2, light transmittance is not a property of interest as such, but has to be converted into a more meaningful measure. In Paper I, two possible estimation methods for converting light transmittance information into basis weight estimates are presented. Both of the methods use scanning basis weight measurement as a reference. The first method, here termed Dynamic validation of the transmittance, is based on Bayesian estimation and random walk stochastic models (Ihalainen et al. 2006). The algorithm also uses continuous calibration for the linear relation between the basis weight and the transmittance. The second method, called Confidence level based reasoning, is based on evaluating the reliability of the measurements and using fuzzy limits for determining the weighting factor for each measurement reading (Näsi 2007). This method does not incorporate a continuous calibration between the basis weight and the transmittance. The aim of the estimation is to provide MD and CD basis weight estimates that can directly be used for monitoring and control purposes without further data processing.

The methods were tested for several disturbance scenarios and the resulting estimates were visually compared with simulated data. The simulated data changed dynamically as the control actions were simulated. The Dynamic validation of the transmittance estimation methods showed more robust performance within the simulated disturbance scenarios than the Confidence level based reasoning estimation method. In particular, the excessive noise in the measurements was harmful for the estimation performance of Confidence level based reasoning, as the high noise content was also seen in the estimates. Therefore, the estimates would require further data processing. Dynamic validation of the transmittance, on the other hand, was able to filter out the excessive noise with appropriate tuning of the method. The manipulation of the tuning parameters can, however, lead to more lagged MD estimates with this method.

Based on the results presented in Paper I, the Dynamic validation of the transmittance method was selected for the further studies as it provides estimates that can be utilized directly for monitoring and control purposes. In Paper II, the
performance of the estimation method, and therefore the potential of using web imaging in estimation, is studied in a more detailed manner. The simulations were restricted to incorporate only the deterministic disturbance scenarios and random variations. No control actions were included in order to be able to focus on the estimation performance. Three disturbance scenarios were simulated: 1) MD/CD separation problem with the presence of fast MD disturbances close to the scanning period, 2) tilted waves that may originate from sudden consistency changes in the pulp entering the headbox, and 3) 2D variation, which is represented as dynamically changing CD disturbances. The latter is used as a test signal for examining the estimation performance against correlated CD variation. The estimation performance is given as the Pearson’s correlation coefficient between the simulated and estimated basis weight maps. The estimation performance of image-based measurement is compared with that of scanner-based measurement. Scanner-based measurement is formed using the exponential moving average filter for the scanner measurement. Fig. 5 presents the estimation performance in the three simulated disturbance scenarios.

![Fig. 5. Estimation performance in simulated disturbance scenarios. Results collected from Paper II.](image)

The correlations presented in Fig. 5 are for the 2D web. Therefore, the MD profile, average CD profile, and residual variation are all included. The two average
properties tend to increase the correlation. The results show that in all three disturbance scenarios image-based estimation provides a more enhanced view of the simulated paper web variations than scanner-based estimation. The results also show that the estimation algorithm applied can efficiently utilize both scanner and transmittance measurements, as the correlations are higher with image-based estimation than with transmittance alone.

The additional results given in Paper II show that in the presence of fast MD variations, the correlation between the MD profile of the simulated basis weight and the estimated basis weight increases from 0.45 to 0.91 when comparing the results with scanner-based measurement and image-based measurement, respectively. Image-based measurement can detect the fast MD variation that is impossible to detect with scanner-based measurement. The disturbance scenario comprising tilted waves with the CD/MD angle of the tilted wave varying between 5 and 75 degrees, shows that the correlation between the residual variation of the simulated basis weight and the estimated basis weight with scanner-based measurement does not exceed a value of 0.28. The corresponding results with image-based measurement show the correlation ranging between 0.49 and 0.62. The disturbance scenario including the dynamically changing CD variation with a period ranging from 1000 s to 100 s, shows that the correlation between the residual variation of the simulated basis weight and the estimated basis weight with scanner-based measurement does not exceed a value of 0.30. The corresponding results with image-based measurement show the correlation ranging between 0.43 and 0.51. Image-based measurement can detect the presence of certain types of residual variation that is very difficult to detect from scanner-based measurement.

3.2 Control

The control algorithms presented in Paper III aim to improve the dynamic bandwidth of CD and MD control. The results presented in Paper IV demonstrate to what extent the dynamic bandwidth can be improved if the control calculations and models are based on image-based measurement instead of scanner-based measurement.

It should be emphasized that the comparison between the control results with scanner-based and image-based measurement is based on the simulated basis weight maps. The results do not aim to measure how much of the detected variation is removed, but to what extent the true (simulated) basis weight variation is controlled. The control behavior therefore depends both on the estimation
performance and the control performance resulting from the estimated control
textmodels and control calculations with an appropriate control interval.

3.2.1 CD control

In Paper III, the CD controller was tested with simulated data, including
dynamically changing CD variation. The CD control model was first identified
from simulated bump tests. The sampling interval of the simulated data as well as
that of the image-based measurement was 1 s. The sampling interval of scanner-

based measurement was 1 scan. With the simulated scanner speed and web width,
the scan time was 17 s, including 1 s for a change in scan direction. The identified
discrete-time models are given in Table 1. The IMC controller time constant was
set at twice the continuous-time model time constant. The control result is obtained
by comparing the temporal CD profile variances of the basis weight in an open loop
and in a closed loop. The results with scanner-based and image-based control are
presented in Fig. 6. In this example, the CD control system with image-based
measurement outperforms the corresponding system with scanner-based
measurement in terms of temporal performance in the tested simulation
environment. Both control systems reduce the average CD profile variance in a
similar manner. Therefore, image-based control reduces the temporal, or residual
variation in particular and should have a higher dynamic bandwidth.

<table>
<thead>
<tr>
<th>Model</th>
<th>Sampling time</th>
<th>Numerator</th>
<th>Denominator</th>
<th>Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated</td>
<td>1 s</td>
<td>0.692</td>
<td>0.308</td>
<td>10</td>
</tr>
<tr>
<td>Image-based</td>
<td>1 s</td>
<td>0.034</td>
<td>0.963</td>
<td>13</td>
</tr>
<tr>
<td>Scanner-based</td>
<td>1 scan</td>
<td>0.272</td>
<td>0.686</td>
<td>3</td>
</tr>
</tbody>
</table>

Paper IV describes how the CD controller was tested using frequency response
tools in order to evaluate the dynamic bandwidth systematically. The models used in
the study are presented in Table 1. The model parameters differ from those used in
Paper III, as the identification was based on a more extensive set of simulations in
Paper IV. A threshold of -6 dB, corresponding to 50% attenuation in the disturbance
amplitude, was chosen to describe the system performance. This performance
measure is here termed the limiting frequency, or the limiting period if presented
in the time domain instead of the frequency domain. Fig. 7 presents the dynamic
disturbance rejection properties of the CD control systems relying on image-based measurement and scanner-based measurement. The dynamic performance indices are collected in Table 2. With image-based control, the limiting period is 410 s, whereas with scanner-based control, the limiting period is 2120 s. The difference is even higher when 90% removal (-20 dB) is concerned; image-based control effectively attenuates disturbances with periods longer than 2140 s, but scanner-based control is only effective if the disturbance period exceeds 11430 s. These numbers correspond to cyclic CD profile changes observed within 35 min and 3 h. If temporal CD disturbances between these two periods are present in a paper machine, the benefit of image-based measurement in the CD control is unquestionable.

Fig. 6. Temporal CD profile variance with scanner-based and image-based control (modified from Paper III, published by permission of TAPPI).
3.2.2 MD control

In Paper III, a control structure utilizing the mean level of CD actuators as a secondary input to the MD control is proposed. The controller belongs to the class of habituating control schemes. The controller structure, CD-assisted MD control, comprises the nominal PI control with Smith predictor and a P controller, where the secondary control signal is dependent on the behavior of the primary input during the transients. In steady state, the secondary input returns to its set point. There is also a predictor for the secondary input in order to cancel the effect of the secondary input to the set point of the primary controller. For Paper IV, the PI control and the Smith predictor were replaced with an IMC and the controller structure was refined with a correction to the controller gain in the inner loop.

The proposed control structure was tested with the simulated data in Paper III. The MD control models were first identified from the simulated bump tests. The sampling interval of the simulated data as well as that of the image-based
measurement was 1 s. The sampling interval of the scanner-based measurement was 1 scan. With the simulated scanner speed and web width, the scan time was 17 s. The identified models for the MD control and the CD-assisted MD control are given in Table 3 and Table 4, respectively. The comparison of the model parameters of the primary and secondary input shows that the observed dynamics are slower for the secondary input with scanner-based measurement. Hence, CD assistance was excluded from scanner-based control. With image-based measurement, the secondary input shows faster dynamics and the CD-assisted MD control may therefore improve the dynamic bandwidth of the MD process. In MD control, it is necessary to evaluate both the reference tracking performance and the disturbance rejection performance. Fig. 8 presents the results for the reference tracking example given in Paper III. The observed MD profiles for the three control structures are given: scanner-based control, image-based control, and image-based control utilizing CD assistance. Also, the control signals for the two latter structures are presented.

![MD profile in reference tracking](image1)

![Control signals in reference tracking](image2)

Fig. 8. Reference tracking performance of MD control (modified from Paper III, published by permission of TAPPI).
In the example, the MD control system with image-based measurement enabling CD assistance outperforms the nominal system with scanner-based measurement in the tested simulation environment. The results also show that image-based control without CD assistance has only a minor effect on the control performance in comparison to scanner-based control. In the disturbance rejection example presented in Paper III, the CD-assisted MD control utilizing imaging measurements resulted in a 54% variance reduction in the simulated MD profile. The corresponding variance reduction for image-based control without CD assistance was 8%. Scanner-based control was not able to attenuate the disturbances and the resulting MD profile had 5% higher variance than the simulated disturbance. Therefore, image-based CD-assisted MD control can attenuate the fast MD variation that is uncontrollable with scanner-based MD control. The results also confirm that the secondary input of the proposed control structure does not affect the primary input and the secondary input is active only during the transients. This can also be seen from the control signals presented in Fig. 8.

| Table 3. Identified models for MD control in Paper III and Paper IV. |
|--------------------------|--------------------------|--------------------------|--------------------------|
| Model | Sampling time | Numerator | Denominator | Delay |
|      |              |           |            |      |
| Simulated | 1 s        | 0.041     | z-0.959     | 30   |
| Image-based | 1 s        | 0.040     | z-0.962     | 39   |
| Scanner-based | 1 scan     | 0.548     | z-0.521     | 2    |

| Table 4. Identified models for CD-assisted MD control in Paper III and Paper IV. |
|--------------------------|--------------------------|--------------------------|--------------------------|
| Model | Sampling time | Numerator | Denominator | Delay |
|      |              |           |            |      |
| Simulated | 1 s        | 1.15      | z-0.308     | 10   |
| Image-based | 1 s        | 0.117     | z-0.937     | 13   |
| Scanner-based | 1 scan     | *         | z-0.786     | *    |

*The CD model of scanner-based measurement is not presented in Paper III.

In Paper IV, the MD control structures are evaluated in the frequency domain. The models used in the study are presented in Table 3 and Table 4. As in the CD simulations in Chapter 3.2.1, the model parameters are identified based on a more extensive set of simulations and the parameters therefore differ from those used in Paper III. The dynamic behavior in disturbance rejection is evaluated based on the same performance indices as in CD control. The dynamic limitations are presented in Table 2. There are only minor improvements in the performance indices between
scanner-based MD control and image-based MD control. However, when utilizing CD-assisted MD control with image-based measurement instead of scanner-based MD control, the limiting period decreases from 1480 s to 430 s. The performance improvement is emphasized when comparing 90% attenuation: the period is decreased from 2 h to 38 min. The frequency responses to the disturbance rejection and the reference tracking for the tested MD control structures are presented in Fig. 9. In reference tracking, a common measure for system performance is the dynamic bandwidth (-3 dB). For scanner-based control, image-based control, and image-based CD-assisted MD control, the dynamic bandwidths are 391 s, 355 s, and 143 s, respectively. The benefits of image-based CD-assisted MD control are obvious in a paper machine where fast MD variations between 38 min and 2 h need to be controlled or substantially faster reference tracking is required.
3.3 Generalization

The results presented in the previous chapters describe the system performance in the selected simulation conditions. Further considerations about how the measurement quality affects the achievable performance both in estimation and control are presented in Paper II and Paper IV. In Paper V, the evaluation is extended to a more complicated CD control task comprising multiple CD profiles and actuator sets.

In Paper II, the effect of the noise content of the transmittance on the estimation performance was evaluated in terms of Pearson’s correlation coefficient. The
results presented in Fig. 10 show how the residual, or 2D variation, with different periods for cyclic CD variation is detected by the estimation method when the noise content of the transmittance is altered. Even when the noise content is at a similar level to the scanning measurement, image-based estimation is still able to detect more 2D variation than scanner-based estimation. It should be noted that no changes to the tuning parameters of the estimation method were made although the noise content was altered.

In Paper IV, the tuning parameters of the estimation method were optimized for the different noise scenarios. The estimation performance was evaluated based on the correlation, but also based on the root-mean-square error (RMSE) between the simulated and the estimated step test signals, in order to investigate the dynamic performance of the estimation. The optimization task was to maximize the balanced correlation of the MD and CD profiles. Alternatively, the optimization could also be based on minimizing the RMSE of the CD and MD responses. The results comprising the optimized performance, median values, and the interquartile range (iqr) from 99 simulations with different noise maps are presented in Table 5. With the proper tuning for each tested noise scenario, both the MD and CD correlation can be kept at a high level. Since the interquartile ranges are also low, there is no significant effect on the estimation performance between the different noise maps. Therefore, the optimized results can be generalized to other noise maps than the one used during optimization. In Paper IV, no significant variations in the process identification performance were found. If the noise content of the transmittance is known and the tuning parameters are altered accordingly, the control performance can also be expected to remain at the same level even though the noise characteristics of the transmittance change.

<table>
<thead>
<tr>
<th>Noise variance</th>
<th>CD, nominal tuning</th>
<th>CD, Optimal tuning</th>
<th>MD, nominal tuning</th>
<th>Optimal tuning and iqr</th>
<th>MD, median</th>
<th>Median and iqr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>-</td>
<td>0.955</td>
<td>0.955; 0.002</td>
<td>-</td>
<td>0.951</td>
<td>0.952; 0.002</td>
</tr>
<tr>
<td>0.1</td>
<td>-</td>
<td>0.952</td>
<td>0.954; 0.002</td>
<td>-</td>
<td>0.958</td>
<td>0.958; 0.001</td>
</tr>
<tr>
<td>0.5</td>
<td>0.854</td>
<td>0.946</td>
<td>0.946; 0.002</td>
<td>0.983</td>
<td>0.958</td>
<td>0.959; 0.001</td>
</tr>
</tbody>
</table>

Table 5. The effect of different noise maps on estimation performance. Estimation performance expressed in Pearson’s correlation coefficient. Results collected from Paper IV.
Fig. 10. The effect of the noise level in transmittance on estimation performance (modified from Paper II, published by permission of NPPRJ).

In Paper V, the original CD control algorithm is extended to handle multiple CD profiles and actuator sets simultaneously. The control problem is therefore more complicated in terms of the size of the system and the interactions between the multiple profiles and actuator sets. The automated tuning of the spatial controller was also proposed. The tuning is based on the control output distance to the saturation limit of the output in order to avoid actuator saturation and control signal clipping. The analysis consists of the simulation results with three possible control strategies: single property control (SP), where competing control actions cannot be avoided, single property control utilizing feedforward compensation (SPFF) and the proposed multiple property control (MP). The performance evaluation was based on the following indices: a performance criterion comparing the open-loop and closed-loop profiles, the cost function of the controller, the profile variances, the actuating effort of the actuator sets, and the number of saturating actuators.

The results collected in Table 6 present the steady-state performance from simulations where Profile1 is the basis weight, Profile2 is the moisture content, Actuator1 is the dilution headbox, Actuator2 is the steam box, and Actuator3 is the rewet shower. The results show how MP control balances the variance between the two properties efficiently. It allows more variation in Profile1 than the two other control strategies, but enables substantially lower variance for Profile2. The MP control strategy decreases the actuating effort substantially as it minimizes the competing control actions. The results also present the optimal solution calculated as a constrained optimization problem with respect to the performance indicator. The optimal result, however, utilizes substantially more actuating effort than any...
of the control strategies studied. This can also be seen from the cost function values that combine the profile variance and the actuating effort.

<table>
<thead>
<tr>
<th>Control strategy</th>
<th>Performance indicator</th>
<th>Cost function</th>
<th>Profile1 variance</th>
<th>Profile2 variance</th>
<th>Saturating Actuator1 effort</th>
<th>Actuator2 effort</th>
<th>Actuator3 effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP</td>
<td>0.5992</td>
<td>1472</td>
<td>0.1361</td>
<td>0.1751</td>
<td>0</td>
<td>25.99</td>
<td>15.02</td>
</tr>
<tr>
<td>SP</td>
<td>0.7455</td>
<td>2170</td>
<td>0.1042</td>
<td>0.3671</td>
<td>10</td>
<td>50.21</td>
<td>39.96</td>
</tr>
<tr>
<td>SPFF</td>
<td>0.5977</td>
<td>1915</td>
<td>0.1042</td>
<td>0.2641</td>
<td>13</td>
<td>50.21</td>
<td>45.84</td>
</tr>
<tr>
<td>Optimization</td>
<td>0.4491</td>
<td>4697</td>
<td>0.0953</td>
<td>0.1575</td>
<td>37</td>
<td>40.67</td>
<td>55.79</td>
</tr>
</tbody>
</table>

The effect of the automated tuning of the spatial controller is indicated in Fig. 11, where the simulation involves dynamic CD variations that will cause input saturation. It can be seen that there are no saturation violations for Actuator3 when the automated tuning is enabled, whereas some inputs are constantly saturated without the tuning. The number of actuator saturation violations during the simulations total 2860 and 5025 with and without automated tuning, respectively. In the former case, all the actuator saturation violations are observed in the dynamic region between MD positions 201 and 800, whilst without tuning, there are also saturation violations after the dynamic region. Based on the results, automated tuning offers a way to avoid some input saturation.

![Fig. 11. Cumulative sum of saturating actuators with and without automated tuning (modified from Paper V, published by permission of NFA).](image-url)
4 Discussion

The results presented in Chapter 3 demonstrate the potential benefits of utilizing web-wide, image-based measurement, such as light transmittance, in paper machine basis weight estimation and control, instead of relying on scanner-based measurement. Utilization of image-based measurement requires feasible computational algorithms for the calibration and data fusion tasks and also poses some new challenges on control algorithms.

Naturally, accurate web-wide measurement would enhance the estimation performance of step-like and uncorrelated CD variations substantially as indicated in Tyler & Morari (1995). Despite the development of web-wide measurements in the paper industry (Francis 1991, Williams et al. 1996, Heaven et al. 2000), such measurement persists to be commercially unsuccessful. The utilization of WIS for imaging the paper web might be a more intriguing option, as it is a technology already installed in many paper machines. However, the reliability of light transmittance measurement and its calibration into basis weight estimates, for instance, decreases the usability of such systems. The calibration is necessary for control purposes for several reasons: First of all, the current actuators in paper machines are dedicated to the control of traditional quality properties. Secondly, light transmittance might be affected by several quality properties. Consequently, performing control actions directly based on light transmittance might compromise the performance of the independent quality property control loops due to competing control actions.

The results presented in Chapter 3.1 show that, in simulated conditions, image-based measurement do enhance the detection of different basis weight variations, such as fast MD variation, correlated CD variation, and tilted waves, which cannot be detected by scanner-based measurement. Tilted, or diagonal, waves have also been detected from the experimental image-based data in Ylisaari & Ritala (2010). If such variations are detected even only from light transmittance images, it may help to diagnose their root causes. Additionally, any information about variations that are undetectable for scanner-based measurement is valuable and could, for example, be utilized in guiding the movement of the scanning sensor (Duncan 2010). The simulation results in Chapter 3.3 additionally indicate that, with the proper tuning of the estimation method, accurate CD and MD basis weight estimates can be provided even though the noise content in the light transmittance is high. This demonstrates the suitability of the applied estimation method for the calibration task.
In the literature, CD control strategies are divided into optimal linear control and MPC. Due to the potentially higher sampling frequency with web-wide measurement, the computational issues of the control algorithms cannot be neglected. MPC designs tend to increase the computational time and may also lead to more conservative control than optimal control strategies (Adegbege & Heath 2011). In this thesis, the CD control was based on optimal control with respect to the spatial direction. The dynamic behavior with the applied LQC+IMC strategy cannot be regarded as optimal, but nevertheless the coupled design stabilized the CD control efficiently. The CD controller was extended in this thesis to handle multiple properties in order to avoid competing control actions between the control loops. This topic has also been dealt with both for MPC and IMC designs, see e.g., Lahouaoula & Gheorghe (2010) and Duncan & Heath (2008). An attempt to consider possible constraints in optimal linear CD control was also made in this thesis. A more comprehensive view of constraint handling within the IMC approach is given in Adegbege & Heath (2011). The results presented in Chapter 3.2.1 concentrate on the dynamic performance of the CD control, whereas most literature sources mainly focus on the spatial performance. With scanner-based measurement, CD control is inefficient in removing cyclic variations occurring faster than 3 h. Since a modern newsprint machine has a production rate of 40 m/s, this would mean over 400 km of produced paper. With image-based measurement, potentially the cyclic CD changes occurring between 35 min and 3 h could be controllable, therefore extending the CD control to variations earlier classified as uncontrollable residual variation. A sudden large process upset in CD is typically corrected within 30 min to 2h, according to Ritala (2009). In Lahouaoula & Gheorghe (2010), such an upset is recovered in less than 10 min. However, in this thesis, the analysis did not cover step-like disturbances. Ultimately, dynamic performance is also dependent on the machine configuration and actuators, measurement locations, and the production rate, which determine the dynamic behavior of the control system.

The utilization of the mean level of the CD actuators as an MD input has been discussed in Hall (1991) in the context of moisture control. Modern dilution profiling actuators and the enhanced sampling frequency with web-wide measurement allow this to be reconsidered in basis weight control as well. The benefits are illustrated in the results presented in Chapter 3.2.2. Based on these results, the separation of this additional MD input from scanner-based measurement was not straightforward, but was achievable through image-based measurement. Therefore, fast cyclic MD variations of between 38 min and 2 h could be controlled and faster reference tracking could be enabled with image-based measurement and
the proposed control strategy. There are naturally certain restrictions for CD-assisted MD control; Hall (1991) writes that the assistance should be designed so as not to diverge the CD performance too much and also some control capability into CD control must always be ensured. In addition, there would most likely be some unwanted disturbances in the process due to the changing amount of dilution water. Usually the dilution water is taken from the wire pit, thus containing some fibers and fillers (Ritala 2009).

The results presented in this thesis are based on a simulated paper machine. However, a simulator cannot be an accurate reconstruction of a real-life process, but more an ideal design of a process. It should be emphasized that in this paper machine simulator, the simulated quality variations, measurement process, and the estimation and control algorithms are independent parts of the simulator. The control actions are based on estimated quality variations and estimated process models. The true basis weight map is, however, used in the performance evaluation. The quality variations simulated are mainly deterministic variations used as test signals. Some of the simulations also use scanner-based data collected from a real newsprint machine as background variation since the data describes the variation levels of the controlled system. The simulated transmittance is a linear combination of three quality variables, but the variations and coefficients have been carefully chosen so as not to make the calibration task too simple. The simulated transmittance has correlations to basis weight at a comparable level with experimental data found by Raunio et al. (2010) and the scanner noise characteristics are in accordance to those reported in Lang & Wasowski (2012). The estimation algorithms studied assume that the measurements can be aligned accurately. This might be very challenging in a real process as the delay is dependent on the machine speed. If the two measurements are mounted in very different locations along the production line, phenomena such as paper wandering and shrinkage will make the alignment even more challenging. Due to these facts concerning the simulation, the results indicate the upper potential of the utilization of web-wide transmittance measurement in a paper machine.

Although the remaining challenges in web imaging would be solved, and the aligning of the measurements would be correct, the methodologies proposed are not completely ready to be implemented into a real process. The control algorithms require appropriate constraint handling or robust tuning in order to avoid excessive control signals and constraint violations. The feasibility of CD-assisted MD control needs to be studied in terms of the operation range of the dilution actuators. In addition, the interactions caused by dilution require more careful analysis. Further,
if image-based measurements are available, for instance only for basis weight control, how should the different control loops be synchronized so that the potentially increased control interval in one loop does not cause short-term variations in the other loops. Future research could also consider alternative data fusion and filtering techniques for the estimation problem.
5 Conclusions

This work presented suitable computational algorithms for the web-wide estimation and control of basis weight variations in a paper machine based on light transmittance and scanning measurement. The performance of the computational algorithms was evaluated in a simulation environment. Using simulation enables information to be obtained without disturbing the normal operation of the process or arranging expensive experiments. The results illustrated the benefits of image-based measurement for monitoring and control purposes in comparison to scanner-based measurement.

In the first part of this work, it was shown that image-based measurement can be utilized to detect basis weight variations such as fast MD variation, tilted waves and dynamic CD variation patterns that are practically undetectable by scanner-based measurement. It was also found that the estimation method could be tuned for accurate CD and MD basis weight estimates for different light transmittance noise content levels. Hence, the light transmittance images with the presented calibration method can improve the basis weight estimation and potentially also allow reconsideration of the control strategies used in profile controls.

The second part of this work concentrated on the dynamic performance of CD and MD profile control. Image-based measurements were found to enable the identification of the basis weight CD control model with substantially faster dynamics. Therefore, CD control was able to handle fast variations that were earlier classified as uncontrollable residual variation. The CD control strategy was extended in this work to handle multiple properties and actuators. The importance of constraint handling in CD control was also shown. Image-based measurement in basis weight MD control does not provide significant performance improvement with the nominal control strategy. However, the control strategy can be developed to account for the mean level of dilution profiling as an additional MD input. The proposed MD control strategy and image-based measurement lead to improved reference tracking and disturbance rejection properties.

The proposed computational algorithms and control strategies indicate the potential of light transmittance measurement in newsprint grade paper machine online estimation and control, under the assumptions made in the simulations. Naturally, the benefits might be less obvious in a real paper machine. The estimation assumes that the imaging and scanning measurements can be aligned accurately. The control strategies need some attention to constraint handling and evaluation of the possible interactions in the paper machine should be conducted.
before the proposed control strategies are ready to be implemented in a real environment.
References


Original publications


Reprinted with permission from TAPPI, the Technical Association of Pulp and Paper Industry (I,III), NPPRJ, Nordic Pulp and Paper Research Journal (II,IV), and NFA, Norwegian Society of Automatic Control (V).

Original publications are not included in the electronic version of the dissertation.
<table>
<thead>
<tr>
<th>No.</th>
<th>Author</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>560</td>
<td>Xue, Qiang</td>
<td>Analysis of near-optimal relaying schemes for wireless tandem</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and multicast relay networks</td>
</tr>
<tr>
<td>561</td>
<td>Rautio, Anne-Riikka</td>
<td>On the stability of carbon nanotube and titania nanowire based</td>
</tr>
<tr>
<td></td>
<td></td>
<td>catalyst materials : from synthesis to applications</td>
</tr>
<tr>
<td>562</td>
<td>Kuokkanen, Ville</td>
<td>Utilization of electrocoagulation for water and wastewater treatment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and nutrient recovery : techno-economic studies</td>
</tr>
<tr>
<td>563</td>
<td>Huusko, Jarkko</td>
<td>Communication performance prediction and link adaptation based on a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>statistical radio channel model</td>
</tr>
<tr>
<td>564</td>
<td>Nguyen, Vu Thuy Dan</td>
<td>Transmission strategies for full-duplex multiuser MIMO communications</td>
</tr>
<tr>
<td></td>
<td></td>
<td>systems</td>
</tr>
<tr>
<td>565</td>
<td>Keränen, Pekka</td>
<td>High precision time-to-digital converters for applications</td>
</tr>
<tr>
<td></td>
<td></td>
<td>requiring a wide measurement range</td>
</tr>
<tr>
<td>566</td>
<td>Koivuranta, Elisa</td>
<td>Optical monitoring of flocs and filaments in the activated sludge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>process</td>
</tr>
<tr>
<td>567</td>
<td>Lohikoski, Päivi</td>
<td>Information processing in global virtual NPD projects</td>
</tr>
<tr>
<td>568</td>
<td>Kauppila, Osmo</td>
<td>Integrated quality evaluation in higher education</td>
</tr>
<tr>
<td>569</td>
<td>Kisko, Anna</td>
<td>Microstructure and properties of reversion treated low-Ni high-Mn</td>
</tr>
<tr>
<td></td>
<td></td>
<td>austenitic stainless steels</td>
</tr>
<tr>
<td>570</td>
<td>Postiila, Heini</td>
<td>Peat extraction runoff water purification in treatment wetlands</td>
</tr>
<tr>
<td></td>
<td></td>
<td>constructed on drained peatlands in a cold climate</td>
</tr>
<tr>
<td>571</td>
<td>Happonen, Tuomas</td>
<td>Reliability studies on printed conductors on flexible substrates</td>
</tr>
<tr>
<td></td>
<td></td>
<td>under cyclic bending</td>
</tr>
<tr>
<td>572</td>
<td>Soderi, Simone</td>
<td>Evaluation of industrial wireless communications systems’ security</td>
</tr>
<tr>
<td>573</td>
<td>Harjula, Erkki</td>
<td>Energy-efficient peer-to-peer networking for constrained-capacity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mobile environments</td>
</tr>
<tr>
<td>574</td>
<td>Tolonen, Arto</td>
<td>Product portfolio management over horizontal and vertical portfolios</td>
</tr>
<tr>
<td>575</td>
<td>Suliman, Isameldin Mohammed</td>
<td>Performance analysis of cognitive radio networks and radio</td>
</tr>
<tr>
<td></td>
<td></td>
<td>resource allocation</td>
</tr>
<tr>
<td>576</td>
<td>Karjalainen, Satu Maaria</td>
<td>Identification of processes leading to long-term wastewater</td>
</tr>
<tr>
<td></td>
<td></td>
<td>purification in northern treatment wetlands</td>
</tr>
</tbody>
</table>

Book orders:
Granum: Virtual book store
http://granum.uta.fi/granum/
Markku Ohenoja

COMPUTATIONAL METHODS FOR EXPLOITING IMAGE-BASED DATA IN PAPER WEB PROFILE CONTROL