AN IMPROVEMENT OF TRANSFER PERFORMANCE IN PAPER FEEDING SYSTEMS

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Abstract: In media-transport system, the slippage between the media and the feeding rollers could significantly degrade the performance of the entire machine. This paper focuses on the analysis of the effect of the normal force and the angular velocity of feeding rollers on the slippage between the paper and the pair of feeding rollers. For this purpose, authors have constructed a testbed and have developed a two-dimensional simulation model to find proper compensation method for the slippage of sheet. Authors also designed and experimentally implemented a fuzzy control system for the paper feeding system that keeps a uniform feeding velocity of paper.

Keywords: media transportation, dynamic modelling, fuzzy control, slippage, the normal force.

1. INTRODUCTION

The media-feeding (or media-transport) system is a key unit in printers, copiers, film-developing machines, ATM's, and many other prevailing consumer electronics. In those machines, sheet materials, such as papers and films, are used as the medium materials. Those media are usually fed into the main processing unit by a pair of rollers or consecutive pairs of rollers, where the rollers are coated with high friction materials. The goal of the media-transport system is to feed a medium material to the main process in a uniform and repeatable manner. A small slippage between the medium and the feeding rollers could result in the irregular feeding and the significant performance degradation of the entire machine. Thus the study on the slippage of the media transport system is essential for improvement of the performance. The slippage between the medium material and the feeding rollers is affected by many parameters, which include the friction coefficient between the feeding rollers and the medium material, the angular velocity of the feeding rollers, and the normal force exerted by the pair of feeding rollers on the medium material. The effect of the roller speed and other parameters on the slippage have been studied and reported by Ryu (2004), Yanabe(2004) but the effect of the normal force has not been fully investigated yet. This paper focuses on the analysis of the effect of the normal force on the slippage between the medium material and the pair of feeding rollers.

Up to date, it is the experimental trial-and-error approach that has been adopted in most of reported researches on the kinematics of media transport system (MTS). However, the trial-and-error method is a very inefficient and inaccurate way for developing and evaluating new media transport systems. It cannot describe the general state of paper being passed through the complex process causing semi-static and dynamic deformation. As a solution, the computer simulation based on multi-body dynamic models is recently developed and suggested for the analysis and the design of the media feeding and separation processes.

In this paper, the authors developed a novel two-dimensional simulation model and an experimental prototype for the media-transporting system, which can feed a sheet of paper with a pair of driving and driven feeding rollers. In the simulation the paper sheet is modelled as multiple rigid bodies interconnected by revolute joints with rotational springs and dampers. Using the simulation model, different normal forces are assumed to be applied on the feeding rollers and the corresponding slippage of the paper being fed through the rollers is calculated by simulation. The modelling and the computation are done using a multi-body dynamic analysis tool called RecurDyn®. To verify the effectiveness of the simulation model experiments are performed using a test-bed of the paper-feeding system. The system parameters used in the simulation are matched with those of the test-bed. In the paper, experimental results are compared with simulation results.

2. EXPERIMENTAL SETUP AND MATERIAL

2.1 Experimental Setup

Figure 1 shows a picture of the experimental setup designed and built by the Media Transport System Research Group at Kyung Hee University. The main feeding part consists of a pair of rolling shafts; the driving and the driven. Two shafts roll against each other through three pairs of rollers, three on each shaft. The rollers fixed on the shafts are coated with urethane for high friction. Figure 2 shows a three-dimensional diagram of the test-bed, where the upper shaft is driving and the lower shaft is driven. Both ends of the driven shaft are pushed up with the same force by a position adjuster mechanism, which is the cylindrical part marked C in Fig. 2. Using the position adjustor we can change the height of the driven shaft and eventually the normal force exerting on the three pairs of the rollers. The normal force being exerted on both shafts is measured by a pair of load cells (SBA-50L, CAS) installed at the both ends of the driven shaft. The angular velocities (V_r) of both shafts are measured by rotary optical encoders (E40S, AUTONICS) installed at the point E in Fig. 2. In order to measure the transfer velocity (V_p) of the paper and the spin of paper, two optical contact sensors (S50-PA, DATASENSOR) are installed at the points mark D in Fig. 1-b.

A step motor of step size 1.8° is mounted at point A to drive the feeding rollers. In order to accurately measure the normal force between the driving rollers and the driven rollers, two sets of load cells are installed at each ends of the driven axis. Signals from the encoders of the two shafts and the contract sensors are acquired by multi-function DAQ board (MF614, HUMUSOFT).

2.2 Properties of Paper Sheet

In this research, high quality papers are used as transferred medium to improve the reliability of experiments. A conventional measure for the quality of the paper is mass of the paper per one square meter (W). The W value of the paper used in this research is 80g/m^2 (Double A). Another conventional measure for the paper quality is the degree of paper's curving ($EI_{V,\ H}$, Nm^2). $EI_{V,\ H}$ value of the paper, which is introduced by Kenji OKUNA et. al.(1994), is related with mass per unit area and calculated as following equations.

$$EI_V = 2.27\times10^{-10}W^{2.93} \tag{1}$$

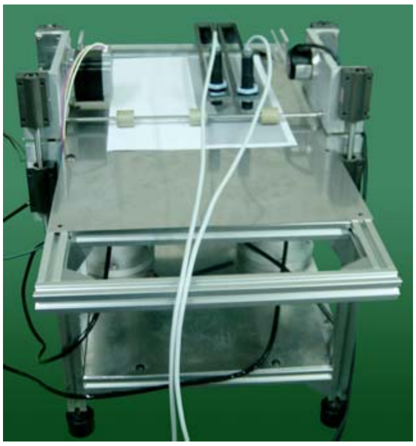

Fig. 1. Picture of MTS test-bed.

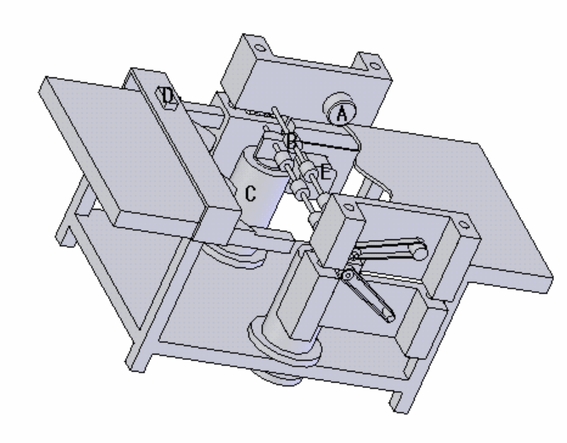

Fig. 2. Three-dimensional diagram of MTS test-bed.

$$EI_H = 1.92\times10^{-10}W^{2.93} \tag{2}$$

The subscript $_V$ represents the vertical direction of the paper and the subscript $_H$ means the horizontal direction of the paper. The width and the height of the paper used in this research are 210 mm and 294 mm, respectively. The thickness of paper is 0.1 mm.

For the measurement of the sheet transport velocity, we printed 460 black lines (thickness 0.3mm, length 70mm) on the paper using a laser printer (1200dpi, ML-6085, SAMSUNG). We used non-contact profile measuring machine (maximum resolution 1 μm, Video-Check-L400, Werth Messtechnik GmbH) for accurate measurement. However, the spaces between the black lines are uneven and unreliable to be used as a measuring basis. In order to compensate the irregularities of the line spacing, we used the measured data for the spacing through input to output vector of Look-Up Table block (Simulink, MATLAB) as correction data of the paper velocity in experiments.

3. MODELLING AND SIMULATIONS

3.1 Basic System Model

The media transport system is modelled to verify factors related to slippage. Figure 3 is a schematic diagram of the MTS model. The slippage is calculated as the difference of the velocities of the media and the driving roller. Therefore, friction forces are very important factor in the slippage analysis. There are three principal contacting surfaces in the MTS model. The first contact surface is between the driving roller and the paper sheet. The second part is between the paper sheet and the guiding track. The third part is between the driven roller and the sheet. The dynamics of each of the contact surface is represented by following equations.

$$I_{G1}\alpha_1 + F_{k1}R_1 = T \tag{3}$$

where, $F_{k1} = \mu_1 N_1 \operatorname{sgn}\left(R_1\omega_1 - v_{sheet}\right)$

$I_{G1} = M_1 R_1^2 / 2$

$v_{sheet}: velocity\ \ of\ \ sheet$

$T: operating\ \ torque\ \ of\ \ driving\ \ roller$

$R_1: radius\ \ of\ \ driving\ \ roller$

$\alpha_1: angular\ \ acceleration\ \ of\ \ driving\ \ roller$

$I_{G1}: moment\ \ of\ \ inertia\ \ of\ \ driving\ \ roller$

$M_1: mass\ \ of\ \ driving\ \ roller$

$$F_{k1} - F_{k2} - F_{k3} = ma_{x\ \ sheet} \tag{4}$$

where, $F_{k1} = \mu_1 N_1 \operatorname{sgn}\left(R_1\omega_1 - v_{sheet}\right)$

$F_{k2} = \mu_2 N_2 \operatorname{sgn}\left(R_2\omega_2 + v_{sheet}\right)$

$F_{k3} = \mu_3 N_3: friction\ \ force\ \ from\ \ guiding\ \ track$

$m: mass\ \ of\ \ paper\ \ sheet$

$$-I_{G2}\alpha_2 = F_{k2}R_2 \tag{5}$$

where, $F_{k2} = \mu_2 N_2 \operatorname{sgn}\left(v_{sheet} + R_2\omega_2\right)$

$I_{G2} = M_2 R_2^2 / 2$

$v_{sheet}: velocity\ \ of\ \ sheet$

$R_2: radius\ \ of\ \ driven\ \ roller$

$\alpha_2: angular\ \ acceleration\ \ of\ \ driven\ \ roller$

$I_{G2}: moment\ \ of\ \ inertia$

$M_2: mass\ \ of\ \ driven\ \ roller$

Equations (3) and (5) can be transformed into (6), (7).

$$F_{k1} = \frac{T - I_{G1}\alpha_1}{R_1} = \frac{T}{R_1} - \frac{I_{G1}\alpha_1}{R_1} \tag{6}$$

$$F_{k2} = -\frac{I_{G2}\alpha_2}{R_2} \tag{7}$$

We substituted (6), (7) into (4) to obtain

$$\frac{T}{R_1} - \frac{I_{G1}\alpha_1}{R_1} - \frac{I_{G2}\alpha_2}{R_2} - F_{k3} = ma_{x\ \ sheet} \tag{8}$$

From (8), it is apparent that the friction coefficients, the normal forces and the velocity of the driving roller affect the slippage of the paper. The normal force and the velocity of the driving roller are designable factors and we focus on those parameters for the improvement of the system.

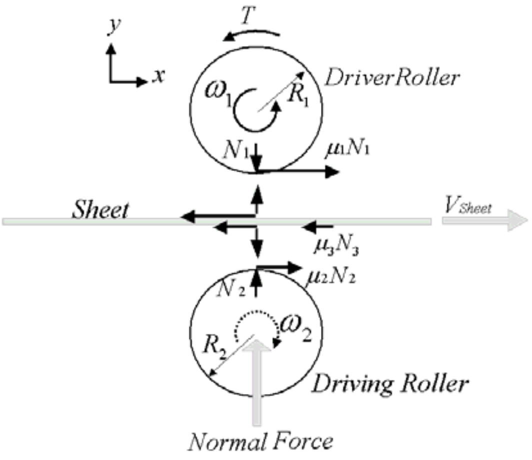

Fig. 3. Schematic diagram of MTS model.

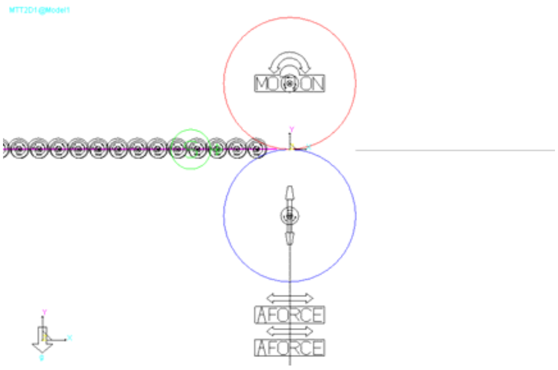

Fig. 4. Two-dimensional model of MTS.

3.2 *Simulation Model Using RecurDyn*

The sheet of paper in MTS is modelled as a two dimensional multi-body dynamic system for the simulation of the paper feeding process. In this research, the two dimensional multi-body dynamic model that was initially introduced by Cho *et. al* (2001) is chosen for a model of the flexible paper, which is shown in Fig. 4. Several researches confirm that the most efficient model of the two-dimensional approximation of a sheet of paper is a series of rigid bars connected with revolute joints and rotational spring-dampers (Ashida, 2002; Cho, 2001). The proposed multi-body model of a paper sheet consists of 99 homogeneous rigid body segments. The length of each segment is 3 mm and the thickness of the paper is 0.1 mm. The density of the paper is 8×10^{-6} g/mm^3 and the Young's modulus is 2250. For the simulation a commercial general-purpose multi-body dynamics analysis tool called RecurDyn is used. In Fig. 4, two feeding rollers, a driving and a driven, are shown. The kinetic friction coefficient between the rollers and the paper is 0.44, which is experimentally obtained from the test-bed (Ryu, 2004).

3.3 *Simulation Results*

Simulations were performed using the given model with different normal forces of 0.1N, 0.3N, 0.7N, and 1N and various speeds of the diving roller of

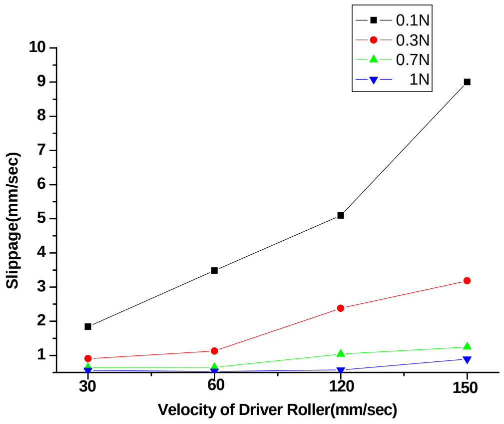

Fig. 5. Calculated slippage between driving rollers and paper sheet (simulation).

30mm/sec, 60mm/sec, 120mm/sec and 150mm/sec. Simulation results are summarized in Fig. 5. As expected, the results show that the slippage decreases as the normal force between rollers increases. Also the slippage increases as the velocity of the driving roller increases.

4. EXPERIMENTS

4.1 Experimental Configurations

Using the test-bed, a series of experiments to measure the slippage of the paper for different normal forces and driving roller velocities are performed. Laser sensors are used to measure the movement of the paper. The laser sensors measure the transport speed of the paper by detecting the evenly spaced black and blank lines on the paper being fed through the rollers. The spot size of the laser sensor unit is 0.2 mm. The pulse signal generated by a motor controller is sent to the driving micro-step motor to control the speed of the driving roller. The linear speed of the driving rollers and the driven rollers are measured by the two encoders attached at the driving axis and the driven axis. The sampling rates for the encoder signals and the laser sensors are set according to experimental condition. The height of the driven axis was adjusted using the cylindrical adjusting mechanism at the each end of the driven axis to produce a desired normal force at the contacting points the rollers. MATLAB Simulink and xPC Target toolbox are used to control the test-bed and to measure the system states. The experimental system consists of a host PC and a target PC to measure and store sensed values. The entire experimental setup is shown in Fig. 6.

4.2 Experimental Results

The experimental condition of normal force of the test-bed includes 0.1N, 0.3N, 0.7N to 1N and the diving roller speed condition includes 30mm/sec, 60mm/sec, 120mm/sec and 150mm/sec. Experimental results are shown in Fig. 7. Though it doesn’t correspond exactly to simulation results, it shows that slippage decreases along with the increment of the normal force between rollers and that slippage increases as of the velocity of the driving roller increases.

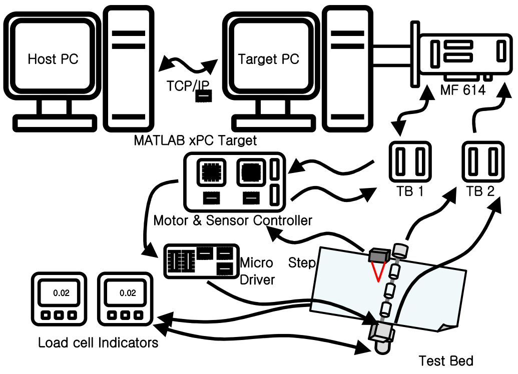

Fig. 6. Schematic diagram of experimental setup.

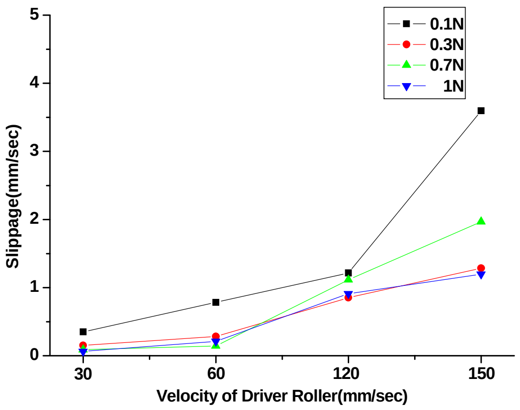

Fig. 7. Measured slippage between driving rollers and paper sheet from experiments.

5. FUZZY CONTROLLER

5.1 Closed-Loop Fuzzy Media Transport System

The simulation results and experimental results shown in the previous sections show that normal force and velocity of driving roller affects the slippage of the sheet. To improve the transport performance of the media transport system by removing the slippage of the media, the authors propose a closed-loop control system. The system is to compensate the slippage by controlling the velocity of driving roller. The authors focus on the roller speed control instead of the control of normal force mainly due to the complexity and the cost of the normal force control. In this paper, the authors used MATLAB Fuzzy toolbox for the design and implementation of a fuzzy controller.

For simulations a real-time discrete control system has been modelled using MATLAB Simulink and RecurDyn applications. Figure 8 shows the block-diagram of the simulation model, where the MTS

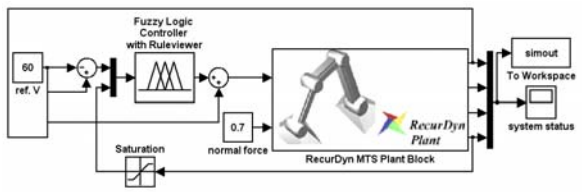

Fig. 8. Block diagram of MTS system with a fuzzy controller (for simulation).

model represented by ‘RecurDyn Plant’ block is implemented using RecurDyn and the control system is implemented using MATLAB. The MATLAB control system components interact with the RecurDyn model and the two sub-models (MATLAB and RecurDyn) share the state information at the discrete time domain. The interaction between the MATLAB component and the RecurDyn components occurs by transporting the control effort calculated from the MATLAB block to the RecurDyn block and also by transporting the calculated paper velocity from the RecurDyn block to the MATLAB control system. The co-simulation using two applications allows us to utilize the powerful capability of RecurDyn in analysing the complex nonlinear dynamic behaviour of the feeding system including the paper model in the MATLAB domain where we can easily design and implement customized control system model. Using the co-simulation approach, we can design and evaluate the control system in more accurate level.

5.2 Simulation Results

Figure 9 shows the simulation results where the velocity of the paper is different from the velocity of the driving rollers under the condition of the normal force of 0.7N and the feeding speed of 60mm/s. Then the control system is simulated using a fuzzy logic under the same condition. The desired velocity of the paper is 60mm/s and the control inputs are the velocity error of the paper and the acceleration of paper. The total number of rules is 7. Figure 10 shows that the fuzzy logic drives the velocity of the paper toward the desired velocity.

5.2 Experimental Results

Using the basic fuzzy logic designed in the simulation, the authors performed experiments on the test-bed with the same operation condition. In experiments, proper signal filtering is used to remove the noise from the sensor signals. Same as the simulation, the authors used MATLAB Fuzzy toolbox and Simulink along with the xPC target application to establish the real-time control system. The experimental results are shown in Fig. 11, where the paper velocity does not converge to the target transport speed. Observing the correlation between the patterns of the driven roller speed and the paper speed, the authors added two more inputs of fuzzy logic to the basic fuzzy logic. The two additional inputs are the velocity and the acceleration of the driven roller. Using the four inputs, new 12 rules of

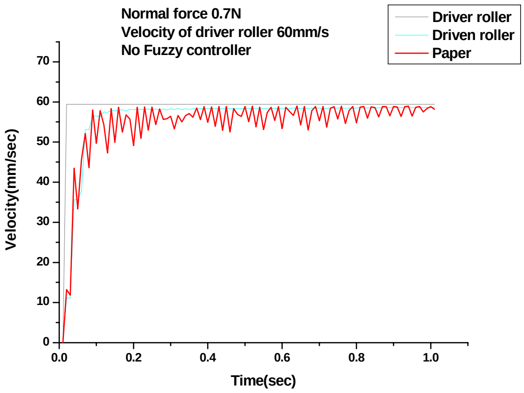

Fig. 9. Difference of velocity at 0.7N normal force from simulation

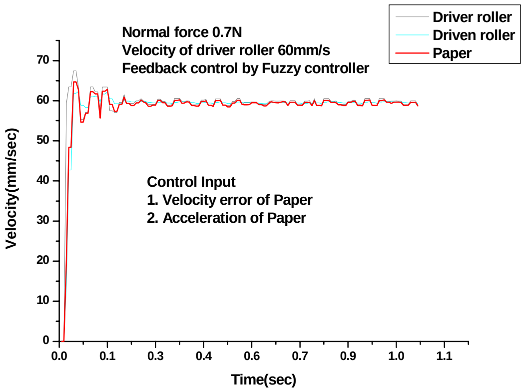

Fig. 10. System response controlled by fuzzy logic from simulation

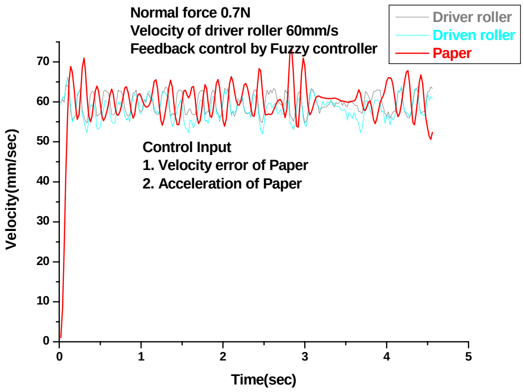

Fig. 11. Response of the system that controlled by two inputs fuzzy logic

the fuzzy logic have been built. Figure 12 represent output of fuzzy inference system and Fig. 13 shows the improved paper transport speed response obtained from experiments.

6. DISCUSSIONS AND CONCLUSIONS

The slippage of the medium in the media feeding part degrades the performance of the whole system. The understanding of the dynamics of the slippage in the

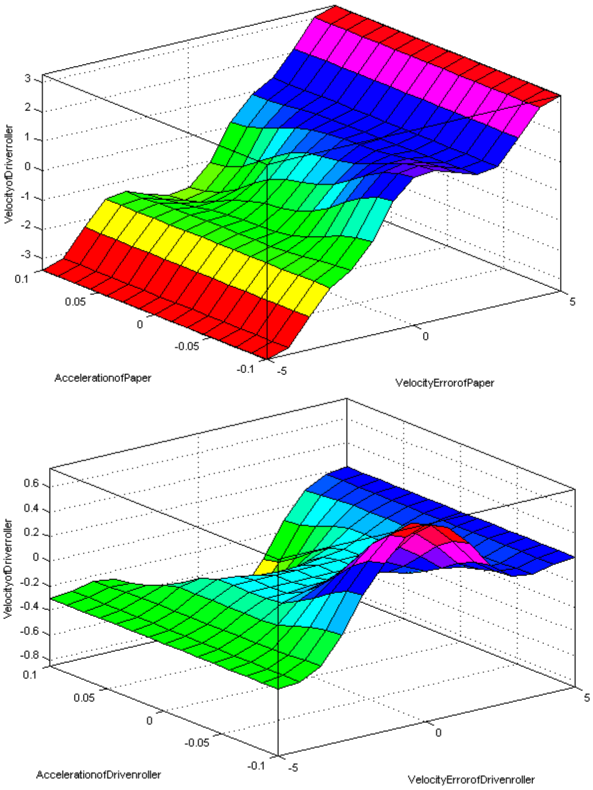

Fig. 12. Output surface graph of fuzzy inference system

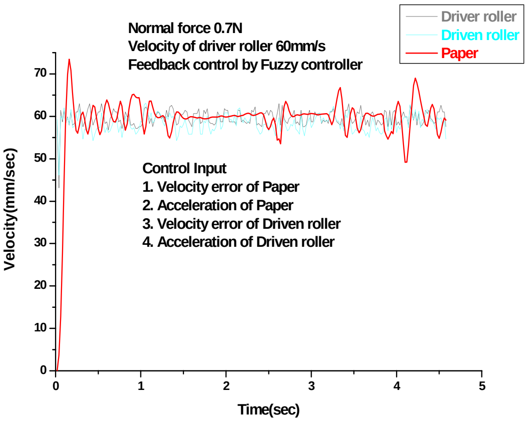

Fig. 13. Response of the system that controlled by four inputs fuzzy logic

feeding system is essential to improve the performance of the media transport system. This paper evaluated the effect of normal force and the speed of the driving rollers on the slippage of the paper and a feedback control system based on the driving roller speed is proposed.

As a simple feeding mechanism, the authors took a pair of shafts that have three pairs of rollers with high friction material where the paper is transferred by the friction force between the paper and the rollers. To study the dynamic behaviour of the system the authors performed a series of simulations using a commercial multi-body dynamic analysis tool called RecurDyn. In the simulation the paper is modelled as a multi-body dynamic system which consists of 99 rigid body segments connected by rotational springs and dampers. The feeding rollers are also modelled in the simulation.

To evaluate the effect of the normal force and the driving roller speed on the slippage of the paper, the authors calculated the slippage of the paper medium for the different normal forces exerted between the two feeding shafts using the simulation model. Also the authors have designed and constructed a test-bed of the paper feeding system, whose system parameters were experimentally estimated and used in the simulations. The slippage of the paper for different normal forces and driving roller velocity was experimentally measured and compared to the simulation results. The measured slippages from experiments show larger magnitudes than the slippages calculated in simulations. The main reason for the difference is considered to be the relatively coarse resolution of the laser on/off sensor used in experiments. Although the laser sensor had 0.3mm resolution, a better resolution is required to measure the fine movement of the paper during the feeding process.

Finally to compensate the slippage of the paper and to achieve a better feeding behaviour of the MTS, the authors developed in simulation closed-loop controllers based on the driving roller speed using fuzzy logic. The developed fuzzy controllers are experimentally implemented. Both the simulation results and the experimental results are included in the paper.

To improve the accuracy and the resolution of the measurement of the paper position a new sensor mechanism is being developed and to be implemented in the future.

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