DIGITAL CONTROL ALGORITHMS FOR WEB-OFFSET INKING

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Abstract: Digital control algorithms have been developed for the integrated web-offset inking control system in the Technical Research Centre of Finland. A new control structure with presetting characteristics has been implemented in a full-scale laboratory press. The presetting of inking screws gives a prompt start of web-offset printing, while maintaining the print quality calls for closed-loop density regulation. After early test printings with a density deviation-based PID-type controller, better feedback rules with a predicting state estimator have been used for inking control. Before the control laws were implemented with a process computer, their feasibility was tested with a desktop computer against the inaccuracies of the web-offset inking model. The control simulations showed that even a rather inaccurate estimator helps to obtain stable control results, if the control interval is not more than 20 press revolutions. The ink consumption of a press zone determines the feedback gain of the corresponding ink screw algorithm. Excessive inking is strictly avoided, because it cannot be cured by the inking actuators, i.e. excessive ink on the rollers disappears only through images printed on paper. The estimator-based digital controller is not sensitive to the delay variations of a press, either, which enables an on-press densitometer to be positioned rather freely in a multi-unit production press.

1. Development of offset inking automation

The aim of modern pre-press operations is to guarantee the prompt start of printing. The presetting of inkers was first used in large newspresses and later the principle has also been proposed for smaller heatset presses. Sofar, the closed-loop control of inking has been tried only in sheet-fed presses. After implementation of conventional controllers for folder register, web edge, dryer temperature, web

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tension etc., also the more complex variables, such as colour register, inking and dampening, should be regulated using modern computers. The colour register controls have advanced rather rapidly, but the development of inking control has been slow at web-fed presses. It may be concluded that the lack of fast on-press densitometers has hampered the realization of closed-loop control of inking in web-fed offset presses. The benefits of inking automation are primarily in quality increase, maybe less so in waste reduction.

The analog methods of classical control theory cannot be easily applied to the control of offset inking. The measurement of the output variable, optical print density, is difficult, because the web runs fast, at speeds up to 10 m/s. The test spot size is on the order of 7 mm x 7 mm, and therefore the measurements must be synchronized very precisely. Owing to the relative nature of density readings, the signal levels of print and reference must be memorized over one cylinder impression. The duration of an impression varies with the press speed and therefore the tuning of conventional time-based controllers, say PID, is laborous during press speed changes. The large number of actuators, for instance more than thirty inking screws in a half-unit, and the unmeasurability of most process states are also significant problems.

Methods of digital control theory have been applied to offset inking in the present work. A prototype control system with simple algorithms was first implemented for process identification and stability studies. The density distribution across the web was measured by an on-press densitometer and then the inking screws and the duct roller were actuated according to observed density deviations. The prototype control system was discussed in the earlier TAGA-Conference (Simomaa, Lehtonen, 1981). The control principles discussed in this paper are used in the Integrated Web-Offset Inking Control system, IWIC, of the Technical Research Centre of Finland.

1.1 Process identification from closed-loop measurements

Several test printings using our prototype control system have provided much closed-loop data concerning the offset inking-to-print density process. In our system the amount of ink feed is governed using a duct roller with inking screws. In the following, the position of screw No. i is given by the discrete variable $u_i(k) = R_i(k)$, where k indicates the running ordinal number of the evaluated instantaneous press revolution. Similarly, the process output is the print darkness, $y_i(k) = D_i(k)$. The dynamic behaviour of a time discrete process with an input u(k) and an output y(k) is given by the difference equation

$$y(k) + a_1 y(k-1) + \ldots + a_m y(k-m) =$$

$$b_1 u(k-d-1) + \ldots + b_m u(k-d-m), \quad (1)$$

where k refers to "press-time". The density evaluation is carried out using the measurement interval of 20 press revolutions.

In order to develop better control algorithms for the offset inking process, we have applied the known linear method of least squares to identify the inking process, Eq. (1), more reliably. We may write for measurements of the process input/output sequence $y(k) = \underline{\psi}^T(k)\underline{\theta}$, where $\underline{\psi}^T(k) = [-y(k-1),\ldots,-y(k-m)|u(k-d-1),\ldots,u(k-d-m)]$ is the vector of the closed-loop measurement results and $\underline{\theta} = [a_1,\ldots a_m | b_1, \ldots b_m]^T$ is the vector of the parameters to be estimated. To obtain an estimation procedure, we have to minimize the cost $V = \underline{e}^T\underline{e}$, where the error vector is $\underline{e} = \underline{y} - \underline{\psi}\underline{\theta}$. Here $\underline{y} = [y(0), y(1),\ldots,y(N)]^T$ and ψ consists of N + 1 measurements $\underline{\psi}(0),\ldots,\underline{\psi}(N)$. After applying the condition $dV/d\theta = \underline{0} \mid \theta = \hat{\theta}$, we obtain the estimate $\hat{\theta} = [\underline{\psi}^T\underline{\psi}]^{-1}\underline{\psi}^T\underline{y}$. Our vector to be estimated was $\underline{\hat{\theta}} = |[\hat{a}_1,\hat{a}_2,\hat{a}_3,\hat{b}_1,\hat{b}_2,\hat{b}_3]^T$ and the measurement interval was 20 revolutons. In computations we used N = 5.

A series of identifications was performed using a desktop computer (HP-85, Hewlett-Packard), which is capable of matrix operations. Twelve groups of possible parameter vectors θ^T were computed and their compatibility with actual closed-loop responses was tested with a "3PR-3" controller simulation program of our prototype, with the improved parameters. The coefficients of the model with the best subjective fitting, as judged by the peak value coincidences with actual measurements at press zone No. 6, were

$$a_1 = -0.487, \quad a_2 = 0.071, \quad a_3 = -0.017$$
$$b_1 = 0.125, \quad b_2 = 0.439, \quad b_3 = 0.492 \quad (2)$$

They correspond to process gain $K_p = 1.86$.

Fig. 1 shows a typical response of print density due to a step-wise increase of inking. The settling "time" of density is about 120 press revolutions, the "dead time" being 20 press revolutions.

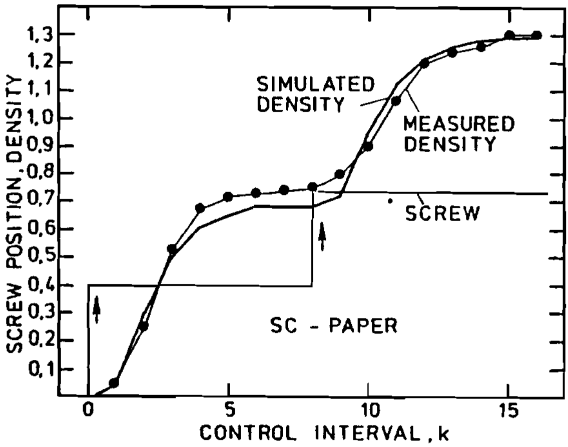

Figure 1. Measured and simulated density responses in press zone No. 6. k = 1 corresponds to 20 press revolutions.

1.2 Computation of optimal control algorithms

The inking model of Eq. (1) may be written(Isermann, 1977) in the known state model

$$\underline{x}(k+1) = \underline{Ax}(k) + Bu(k)$$
$$y(k) = \underline{Cx}(k), \tag{3}$$

where the matrixes of an estimator normal form are

$$\underline{A} = \begin{bmatrix} 0 & 0 & -a_3 & b_3 \\ 1 & 0 & -a_2 & b_2 \\ 0 & 1 & -a_1 & b_1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$\underline{B} = [0 \quad 0 \quad 0 \quad 1]^T$ and

$\underline{C} = [0 \quad 0 \quad 1 \quad 0]$.

We note that $y(k) = x_3(k)$ and $u(k) = x_4(k+1)$. The model delay is one unit of k. The model is schematically shown in the upper part of Fig. 2.

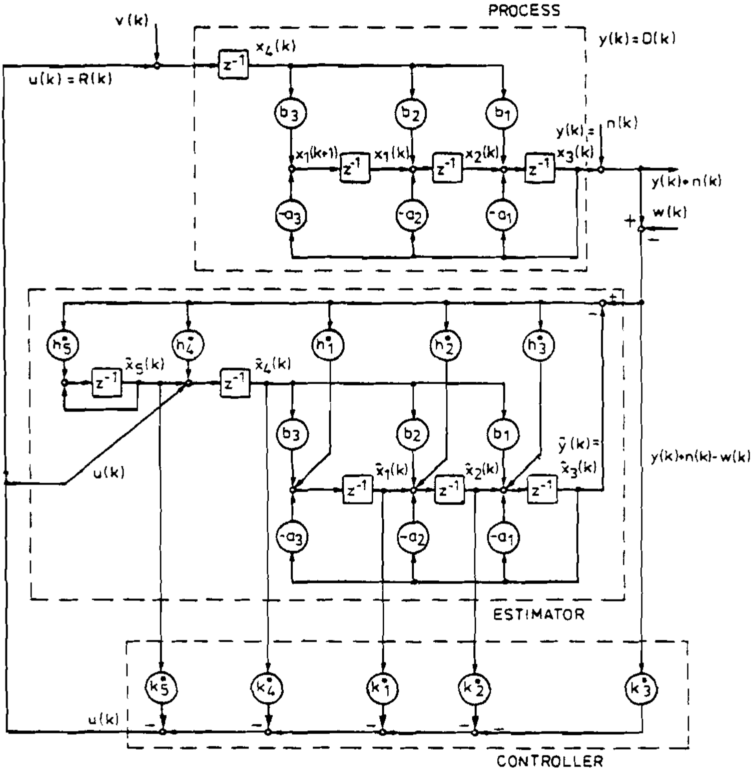

Fig. 2. Model of an optimum state controller with an estimator.

We search for a feedback control u(k) which brings the process to state $\underline{x}(N) \approx \underline{0}$ and minimizes the quadratic criterion

$$I = \underline{x}^T(N)\underline{Qx}(N) + \sum_{k=0}^{N-1} [\underline{x}^T(k)\underline{Qx}(k) + \underline{u}^T(k)\underline{ru}(k)], \qquad (4)$$

where

$$\underline{Q} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

in order to select $y(k) = x_3(k)$ to be included in the criterion I. r is the cost of control $u(k)$.

The known minimization procedure (Kneppo, 1976) with $N \to \infty$ leads to the time invariant control law

$$u(k) = -\underline{k}^T \underline{x}(k), \tag{5}$$

where $\underline{k}^T$ is obtained from

$$\underline{k}^T = [\underline{r} + \underline{B}^T \underline{PB}]^{-1} \underline{B}^T \underline{PA}. \tag{6}$$

The matrix $\underline{P}$ is computed using the recursive Riccati difference equation

$$\underline{P}_{N-j} = \underline{Q} + \underline{A}^T \underline{P}_{N-j+1} [\underline{I} - \underline{B}(r + \underline{B}^T \underline{P}_{N-j+1} \underline{B})^{-1} \underline{B}^T \underline{P}_{N-j+1}] \underline{A}, \tag{7}$$

where $\underline{I}$ is the unit matrix.

The computation starts from an initial matrix $\underline{P}_N = \underline{Q}$; $N = 30$ with $j = 1$ is a convenient starting level.

1.3 Construction of the state estimator

The states of the inking process Eq.(3), cannot be measured, and therefore we have constructed an estimator, according to Kneppo (1976), of increased order for external disturbances

$$\underline{\hat{x}}(k+1) = \underline{A}^* \underline{\hat{x}}(k) + \underline{b}^* \underline{u}(k) + \underline{h}^* [y(k) - w(k) - \underline{c}^{*T} \underline{\hat{x}}(k)], \tag{8}$$

$$\text{where } \underline{A}^* = \begin{bmatrix} 0 & 0 & -a_3 & b_3 & 0 \\ 1 & 0 & -a_2 & b_2 & 0 \\ 0 & 1 & -a_1 & b_1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

$\underline{b}^* = [0 \quad 0 \quad 0 \quad 1 \quad 0]^T,$
$\underline{c}^* = [0 \quad 0 \quad 1 \quad 0 \quad 0]^T,$
$\underline{h}^* = [h_1^*, h_2^*, h_3^*, h_4^*, h_5^*]^T$ and $w(k)$ is the target level.

The structure of the estimator is shown in Fig. 2.

We have computed the numerical values of the correction vector h^* using the recursive rule (Kneppo, 1976)

$$\underline{h}_{N-j}^{*T} = [\underline{c}^{*T} \underline{P}_{N-j+1}^{*} \underline{c}^{*} + r^{*}]^{-1} \underline{c}^{*T} \underline{P}_{N-j+1}^{*} \underline{A}^{*T} \quad \text{with} \tag{9}$$

$$\underline{P}_{N-j}^{*} = [\underline{A}^{*T} - \underline{c}^{*} \underline{h}_{N-j}^{*T}]^T P_{N-j+1}^{*} [\underline{A}^{*T} - \underline{c}^{*} \underline{h}_{N-j}^{*T}] +$$

$$Q^{*} + \underline{h}_{N-j}^{*} r^{*} h^{*T}{}_{N-j} \tag{10}$$

The starting matrixes used were

$$\underline{P}^{*}(\text{start}) = \underline{Q}^{*} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 25 \end{bmatrix} , \quad r^{*} = 5. \tag{11}$$

The control matrix is $\underline{k}^* = [k_1^* k_2^* k_3^* k_4^* k_5^*]^T$. The coefficients $k_1^*, \ldots, k_4^*$ are obtained from Eq. (6), $k_5^* = 1$. The final control algorithm is then

$$u(k) = -k_1^* \hat{x}_1(k) - k_2^* \hat{x}_2(k) - k_3^* [y(k) + n(k) - w(k)]$$

$$-k_4^* \hat{x}_4(k) - k_5^* \hat{x}_5(k), \tag{12}$$

where $y(k)$ is the output with noise $n(k)$, $w(k)$ being the target level.

The choice $r^* = 5$ gave the correction vector $\underline{h}^* = [0.442,\ 0.753,\ 1.277,\ 0.869]$ for our inking model with parameters of Eq. (2).

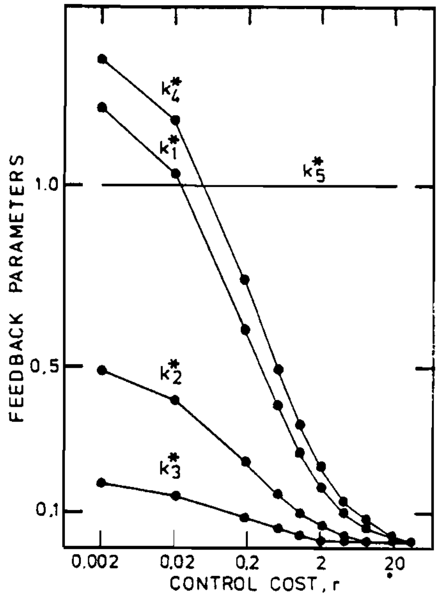

Fig. 3. Feedback coefficients of an optimum state control algorithm.

The vector $\underline{k}^*$ was computed using cost factors r = 0.002 to 32. The components k_1^*, k_2^*, k_3^*, and k_4^* are plotted in Fig. 3. It is interesting to see that the control law converged towards a trivial law

$$u_{trivial}(k) = -\hat{x}_5(k), \tag{13}$$

when r was increased.

1.4. Computer simulations with the optimal controller

We have made several control simulations of the inking process, given by the parameters of Eq. (2), using the control algorithm of Eq. (12). The control interval used was 20 press revolutions. The controller performance was studied by introducing a step-wise change to the target level w(k); w(k) = 0 for k = -1, -2, -3, etc. and w(k) = 1 for k = 0,1,2,3 etc. The process gain is K_p = 1.86 and so the final value of control is $u(\infty)$ = 0.54.

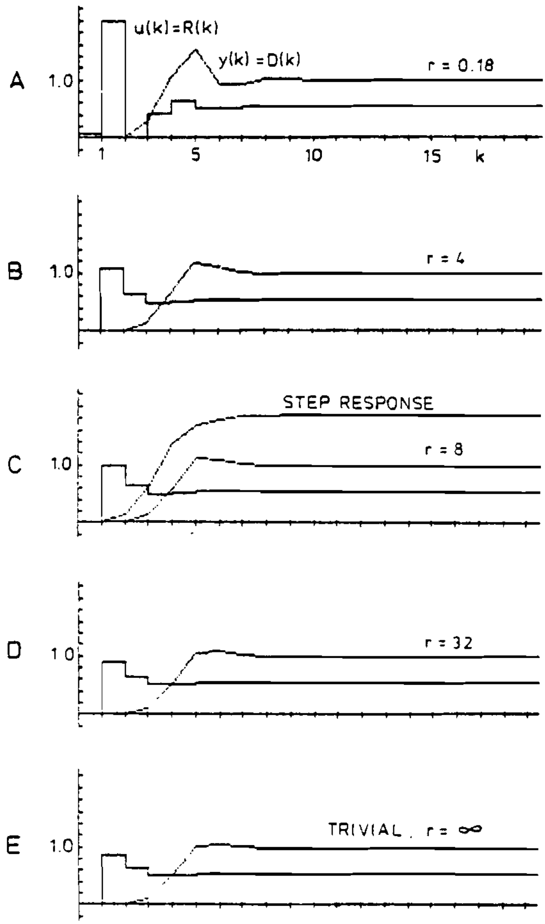

Fig. 4. Simulations of controller step responses with varying cost values.

The computing was done with an HP-85 and the plots were made using its printer.

The effect of the control cost r, Eq. (4), was first studied. According to Fig. 3, r had a strong effect on the control vector $\underline{k}^*$. The plots of Fig. 4 show different responses of the controller, when r was varied from 0.18 to 32. Plot E shows the step response of a trivial controller, Eq. (13). In plot C, also the direct step response of the process is shown. In general, these closed-loop responses show a slight overshoot, but no significant oscillatory fluctuations remain.

In simulations for Fig. 4,the "true" model was used for the process response computations. In Fig. 5 the controller with r = 8 was ordered to control a falsified process, i.e. in plot F the actual process gain was only 0.5 K_p etc., while the estimator was constructed for process gain $1 \cdot K_p$. The controller showed integrating properties with the subsensitive processes, whereas an oscillatory behaviour dominated in case I. The behaviour of the trivial controller was essentially similar, and it is not plotted here.

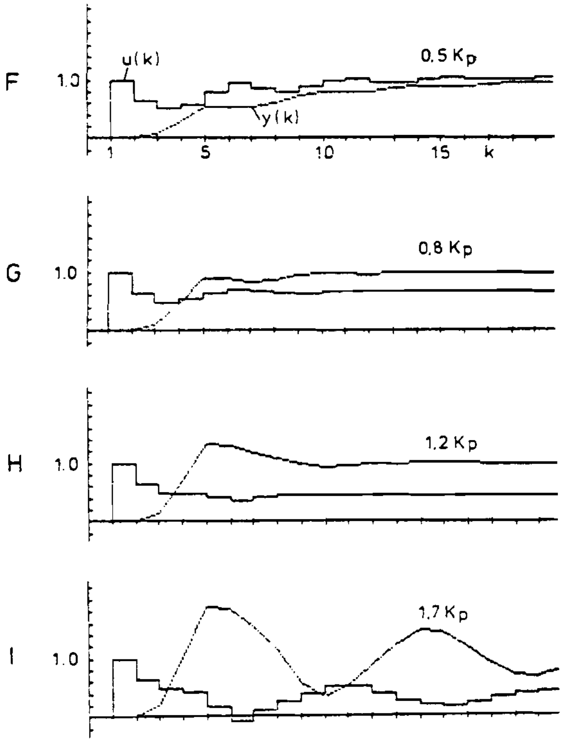

Fig. 5. Simulations of controller step responses. The process gain was varied.

The effect of erroneous dead-time was also studied. In Fig. 6 case N shows the control response without an artificial shift of the process delay. In this case r = 4. Increasing the delay caused a "hill"-like distortion in the control response. A delay error of + 0.6 intervals corresponds to the error of 12 press revolutions. Shortening of the delay, on the other hand, led to slight oscillations as is shown in case K of Fig. 6.

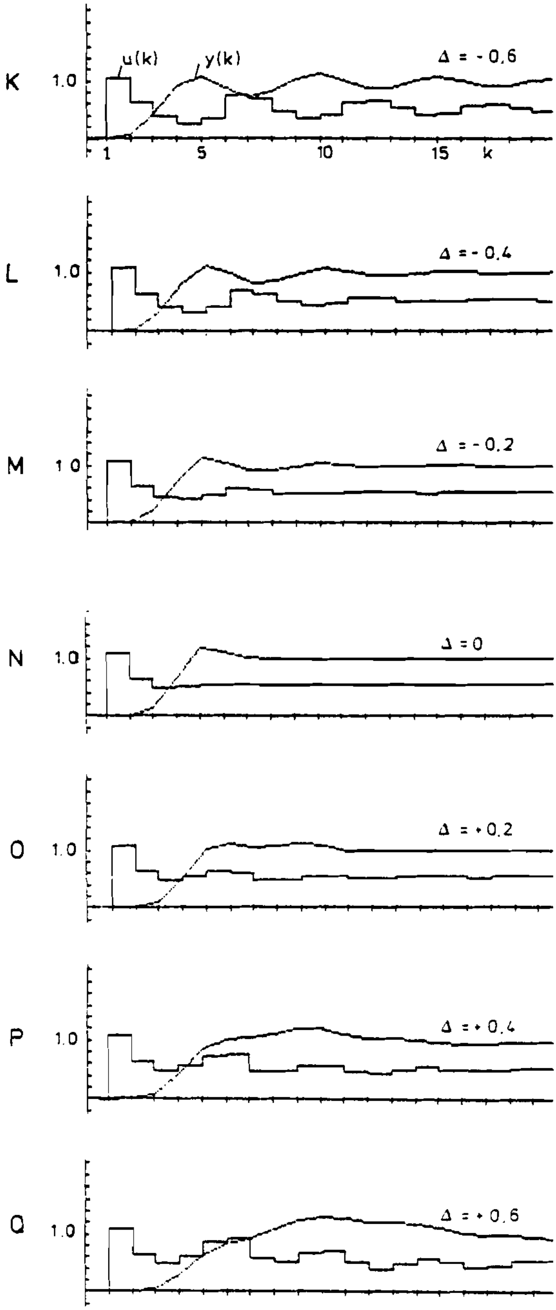

Fig. 6. Simulations of controller step responses. The process delay was varied.

The control responses of Fig. 4, 5, 6 are to be compared with the response of Fig. 7, obtained with the "3PR-3" algorithm of our prototype system. The simulated control response of Fig. 6 shows the typical oscillatory behaviour of a deviation-based PID-type controller. As a consequence, we may conclude that the given state controller is a feasible choice for closed-loop control of the offset inking process.

For presetting of the inker, the screws are positioned according to the zone-wise ink consumption before starting the press. Before the control action starts, also the state of the process estimator, Eq. (8), must be preset to the corresponding level.

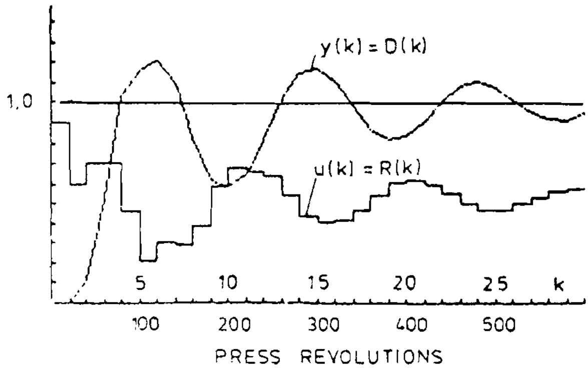

Fig. 7. Simulation of a "3PR-3" controller step response

1.5 Future development

The nonlinearity between the ink feed and print density can be partially evaded when the method of reflectance control is employed. Instead of the density $D = \log_{10}(I_o/I)$, the linear proportion of light intensities, I_o/I, can be used for the process identification, and as a basis for the closed-loop control.

The crisscross modeling of screw positions R_{i-1}, R_i, R_{i+1} to density D_i may also diminish the necessity of control cautiousness.

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