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Multivariable Control Applied to Temperature and Humidity Case Study: Neonate incubator

M. A. Zermani, E. Feki and A. Mami

Abstract—**This study presents multivariable control strategies for humidity and temperature for neonate incubator. This process is TITO system (Two Input Two Output). Identification process of incubator is the first step for design and implementation controller. An experiment method is proposed to determine the transfer function matrix, which decouples the TITO system into four independent loops. Discrete-time system transfer matrix parameters were estimated in real time by the least-squares method. Secondly we take into account couplings between outputs and we consider a decoupling controller to eliminate the strong interaction. After that we develop a generalized predictive decoupled control. At last the simulation results demonstrate the effectiveness of this proposed strategy.**

I. INTRODUCTION

In the first few weeks, premature neonate has a greater risk of complications when he exposed to the unprotected environment [1]. Because, they do not have the developed thermal regulatory control to maintain their body temperature [2] [3]. For many years, incubators are used to produce healthful micro-environment in order to reduce new born heat loss. Temperature is one of the most important factors that need to be maintained with a minimum variation. But only temperature control is not sufficient to provide comfortable environment. Also, the relative humidity control is very important to reduce water loss in newborn infants. Therefore, from control systems viewpoint, an incubator is a system where the temperature and humidity are the main variables to be controlled [4]. Furthermore, the current commercial devices use a passive humidification system, which humidity produced evaporation of water by heating it in the water container [5]. But this method cannot provide a high humidity level at low temperature such as in the range of 23-38 degree.

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For this reason, we have developed a new humidification system based on a nebulizer [6] [7].

Consequently, this process becomes a TITO system (Two Input Two Output) and the actuators have physical limitations, leading to constraints on the inputs and their derivatives. Indeed, couplings between temperature and humidity are very important. The newest incubators, such as the Drager Isolette C2000, use a proportional integral differential (PID) control algorithm to drive the servo control system [8]. Mostly PID is the simplest solution to control these systems. But these controllers do not offer satisfactory control because of interactions. Also the tuning of PID is complicated when they are used in MIMO systems.

Generalized predictive control appears to be attractive solution in multivariable process control [9] [10]. However, these controllers cannot solve problems with strong interaction. In that case, decoupling can perfectly achieved by adding interaction compensators to controllers [11]. In this work, the idea of [7] [12] is extended to TITO systems with couplings between temperature and humidity and with constraints inputs.

This paper is organized as follows. Section 2 presents incubator description, modeling and validation. Section 3 describes the proposed control strategy formulation. Section 4 presents the simulation results. Finally, section 5 presents the conclusions.

II. DESCRIPTION, MODELING AND VALIDATION OF THE INCUBATOR

A. Description

A neonatal incubator is, usually, a small (approx- imately: 0.5 x 0.5 x 1 m^3) cabinet with transparent walls so that the infant can be easily observed. The device may include an AC-powered heater, a fan to circulate the warmed air, a container for water to add humidity and access ports for nursing care. With the technology available currently, incubators use microprocessor-based control systems to create and maintain the ideal microclimate for the preterm neonate.

In this work, we recovered an incubator from Maternal and Neonatal Unit of Rabta-Tunisia. After that, we replaced the passive humidifier by an external block based on a ultrasonic nebulizer which is an instrument for converting a liquid into a fine spray.

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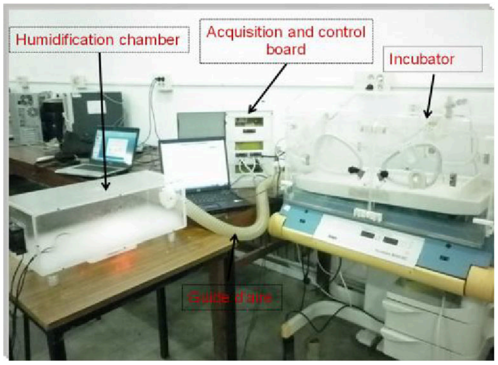

Figure 1. Real process of neonatal incubator with experimental arrangement for active humidification.

This system is able to increase the humidity to 80%. Also we developed a microcontroller-based system devoted to control the humidity and the heating of the newborn incubator. The system developed measures the air temperature and the humidity by tow sensors LM35 and SY-230 [13]. Then, these data were exported to a microcomputer to be analyzed.

B. Modeling

An experimental method is proposed for modeling of the TITO system. The incubator system has two inputs and two outputs.

The inputs to the system are:

U1: control signal applied to the heater,

U2: control signal applied to the nebulizer.

The outputs are:

Y1: temperature value output signal,

Y2: humidity level output signal.

The transfer function matrix of the incubator system can be expressed as follow:

$$\begin{bmatrix} Y_1(k) \\ Y_2(k) \end{bmatrix} = \begin{bmatrix} G_{11}(z) & G_{12}(z) \\ G_{21}(z) & G_{22}(z) \end{bmatrix} \begin{bmatrix} U_1(k) \\ U_2(k) \end{bmatrix} + \begin{bmatrix} e_1(k) \\ e_2(k) \end{bmatrix} \quad (1)$$

The input-output relation of the system is shown in Fig.2

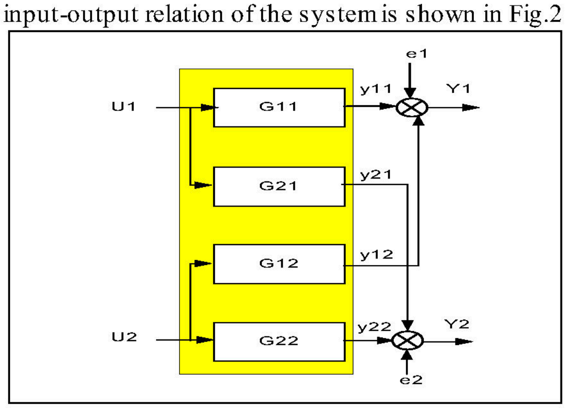

Figure 2. Input-output model of incubator system.

G11 is a transfer function showing the relation between input U1 and output y11. Likewise, G12 is the transfer function that shows the effect of input U2 to output y12, G21 indicates the effect of input U1 to y21; G22 indicates the effect of input U2 to output y22.

The transfer functions of the various subsystems are described as follow:

$$y_{ij}(k) = \frac{z^{-dij} B_{ij}(z^{-1})}{A_{ij}(z^{-1})} U_i(k-1) \quad (2)$$

$$\begin{aligned} Y_1(k) &= y_{11}(k) + y_{12}(k) + e_1(k) \\ Y_2(k) &= y_{22}(k) + y_{21}(k) + e_2(k) \end{aligned} \quad (3)$$

Where i and j are the level indices i, j = {1, 2} and A_{ij}, B_{ij} and C_{ij} are polynomials:

$$\begin{aligned} A_{ij}(z^{-1}) &= 1 + a_1 z^{-1} + a_2 z^{-2} + \cdots + a_{na} z^{-na} \\ B_{ij}(z^{-1}) &= b_0 + b_1 z^{-1} + b_2 z^{-2} + \cdots + b_{nb} z^{-nb} \\ C_{ij}(z^{-1}) &= 1 + c_1 z^{-1} + c_2 z^{-2} + \cdots + c_{nc} z^{-nc} \end{aligned} \quad (4)$$

The transfer functions were obtained by means of experimental tests through the input, the output data collection and the later numeric treatment of this information. For multivariable open loop experiments, the usual practice is to apply mutually independent pseudo-random binary signals (PRBSs) to all the manipulated variables of the plant.

All experimental data were recorded with a sampling period of 20 seconds. A set of models is developed by setting the maximum number of poles to 4 na, nb of zeros 4, the maximum order of the polynomial perturbation nc 2 and the maximum delay time nk 10. The development of all models is achieved by combining the coefficients na, nb, nc and nk The selection of the appropriate orders of the ARIAMX model is determined according to a validation criterion proposed by (Hagenblad et al., 1998) is based on the analysis of the prediction error and the variance of the measured output. This involves comparing the adjustment of new data estimated with experimental data while taking into account the dynamics of output measured on the process.

To find G11(z) an input U2 =0 is applied and the relation between input U1 and output Y1 =y11 is found.

An equivalent equation in differential form can be written:

$$\begin{aligned} Y_1(k) = {} & -a_1 Y_1(k-1) - a_2 Y_1(k-2) + b_1 U_1(k-d-1) + b_2 U_1(k-d-2) \\ & + c_1 \xi_1(k-1) + c_2 \xi_1(k-2) \end{aligned} \quad (5)$$

The output equation can be obtained as below:

$$\begin{aligned} Y_1 &= \theta_1 . \phi_1 \\ \theta_1 &= [-a_1 \quad -a_2 \quad b_2 \quad b_2 \quad c_1 \quad c_2] \\ \phi_1 &= [Y_1(k-1) \quad Y_1(k-2) \quad U_1(k-1-d) \quad U_1(k-2-d) \quad \xi_1(k-1) \quad \xi_1(k-2)]^T \end{aligned} \quad (6)$$

The Least squares algorithm with projection is as follow:

$$P(k) = \frac{1}{\lambda_1}[P(k-1) - \frac{P(k-1)\varphi_{ij}^T(k)P(k-1)}{\frac{\lambda_1}{\lambda_2} + \varphi_{ij}(k)\varphi_{ij}^T(k)P(k-1)}] \quad (7)$$

$$K(k) = P(k)\varphi_{ij}(k) \quad (8)$$

$$\theta_{ij}(k) = \theta_{ij}(k-1) + K(k)(y_{ij}(k) - \varphi_{ij}(k)^T\theta_{ij}(k-1)) \quad (9)$$

To found G12 (z), G21 (z) and G22 (z), a same calculation of G11(z) are used.

At the end of the experiments, the matrix elements of the system transfer function are below:

$$G(z) = \begin{bmatrix} \frac{5.8278e\text{-}005z^{-3} + 9.3029e\text{-}004z^{-4}}{1\text{-}0.5962z^{-1}\text{-}0.3984z^{-2}} & 0 \\ \frac{2.392e\text{-}005z^{-1} + 3.622e\text{-}005z^{-2}}{1-1.981z^{-1} - -0.9803z^{-2}} & \frac{0.00203z^{-3} + 0.00088z^{-4}}{1-0.5091z^{-1} - 0.4262z^{-2}} \end{bmatrix} \quad (10)$$

C. Validation

The model validation is performed by comparing the simulation results with real results from the incubator.

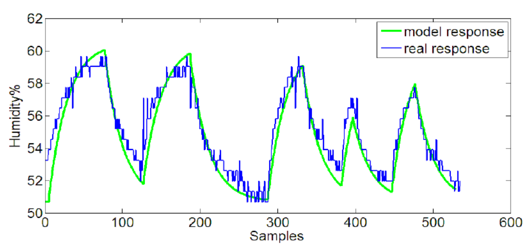

Figure 3. Real and estimated humidity G_{22}.

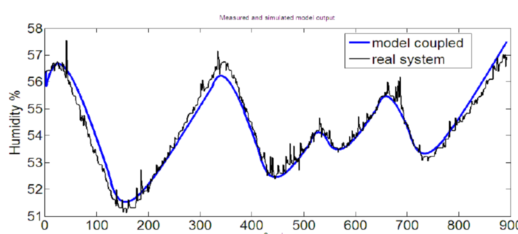

Figure 4. Real and estimated humidity G_{21}.

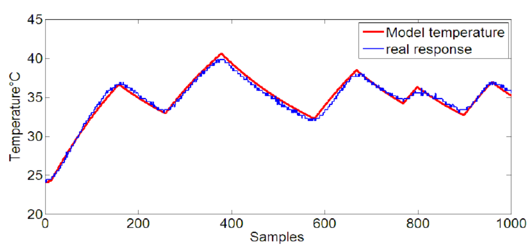

Figure 5. Real and estimated temperature G_{11}.

As it is clear from the structure of the identified model, the temperature variation is almost not related to the change in moisture level (G12=0), and this weak relation can be modeled as a disturbance to the system. The other components are simply modeled with a second order system with a time varying delay. This structure of the model can be used as a start up model for an adaptive GPC synthesis as future work.

III. CONTROLLER DESCRIPTION

A. Cost Function

The generalized predictive control based on the minimization of a quadratic criterion on a sliding horizon, which involves a term related to the difference between the predicted output sequence and the sequence of future control [14]. The criterion is given by the following relation:

$$J_i = \lambda_{yi}\sum_{t=N_i}^{HP_i}[y_{C_i}(k+t) - \hat{y}_i(k+t)]^2 + \lambda_{ui}\sum_{t=1}^{N_{C_i}}\Delta u_i^2(k+t-1) \quad (11)$$

With:

- $\hat{y}_i(k)$: the output value predicted at time k,
- $y_{C_i}(k)$: the set points values at time k,
- $\Delta u_i(k)$: the increment of control at time k,
- N_i : The minimum prediction horizon,
- HP_i : The maximum prediction horizon,
- N_{C_i} : The control horizon,
- λ_{ui} : The control-weighting factor.
- λ_{yi} : The error weighting factor.

B. Prediction of the System Output

The approach of generalized predictive control is based on a dynamic model of type CARIMA (Controlled Auto-Regressive Integrated Moving Average), given by the following form:

$$A_i(z^{-1})y_i(k) = z^{-d_i}B_i(z^{-1})u_i(k-1) + C_i(z^{-1})\frac{\xi_i(k)}{\Delta(z^{-1})}$$
$$y_{F_i}(k) = F_i(z^{-1})y_i(k) \quad (12)$$

With $\Delta(z^{-1}) = 1 - z^{-1}$ corresponds to an integral action.

Using (12), the output at time (k+t) will be:

$$y_{F_i}(k+t) = \frac{F_i(z^{-1})B_i(z^{-1})}{A_i(z^{-1})}u_i(k+t-d_i-1) + \frac{F_i(z^{-1})C_i(z^{-1})}{A_i(z^{-1})\Delta(z^{-1})}\xi_i(k+t) \quad (13)$$

By applying the Euclidean algorithm on the second term of (13), we get:

$$\frac{C_i(z^{-1})}{A_i(z^{-1})\Delta(z^{-1})} = L_t(z^{-1}) + z^{-t}\frac{G_t(z^{-1})}{A_i(z^{-1})\Delta(z^{-1})} \quad (14)$$

Using (13) and (14) and we assuming that the term related to the disturbance is zero, the optimal predictor of the output is written as follows:

$$\hat{y}_{F_i}(k+t) = \frac{L_t(z^{-1})F_i(z^{-1})B_i(z^{-1})\Delta(z^{-1})}{C_i(z^{-1})}u_i(k+t-d_i-1) + \frac{G_t(z^{-1})}{C_i(z^{-1})}y_{Fi}(k) \quad (15)$$

A second Diophantine equation decompose the predictor in two terms: a first term based on the current output, old orders, the system output and a second term dependent on future orders.

$$\frac{\sigma_i(z^{-1})}{C_i(z^{-1})} = H_t(z^{-1}) + z^{-t+d}\frac{R_t(z^{-1})}{C_i(z^{-1})} \quad (16)$$

With:

$$\sigma_i(z^{-1}) = L_t(z^{-1})F_i(z^{-1})B_i(z^{-1}) \quad (17)$$

The optimal predictor of the output is written as follows:

$$\begin{aligned}\hat{y}_{F_i}(k+t) &= H_t(z^{-1})\Delta(z^{-1})u_i(k+t-d_i-1)\\ &+\frac{G_t(z^{-1})}{C_i(z^{-1})}y_{Fi}(k)+\frac{R_t(z^{-1})}{C_i(z^{-1})}\Delta(z^{-1})u_i(k-1)\end{aligned} \quad (18)$$

Where: $H_t(z^{-1})$, $G_t(z^{-1})$, $R_t(z^{-1})$ et $L_t(z^{-1})$ are polynomial solutions to the Diophantine equations [9].

The matrix formulation is represented as follows:

$$\hat{Y}_i(k) = \hat{H}\Delta U_i(k) + \frac{\hat{G}(k)Y_i(k)}{C_i(z^{-1})} + \frac{\hat{R}\Delta U_i(k-1)}{C_i(z^{-1})} \quad (19)$$

With:

$$\Delta U_i = [\Delta u_i(k)\cdots\Delta u_i(k+N_C-1)]^T \quad (20)$$

$$\hat{G} = [G_{1+d}(z^{-1})\cdots G_{HP_i+d}(z^{-1})]^T \quad (21)$$

$$\hat{R} = [R_{1+d_i}(z^{-1})\cdots R_{HP_i+d_i}(z^{-1})]^T \quad (22)$$

$$\hat{H} = \begin{pmatrix} h_0 & 0 & \cdots & 0\\ h_1 & h_0 & \cdots & 0\\ \vdots & \vdots & \vdots & \vdots\\ h_{HP_i-1} & h_{HP_i-2} & \cdots & h_{HP_i-N_{Ci}}\end{pmatrix} \quad (23)$$

C. Law Order

We can write the criterion J in matrix form:

$$J_i = [\hat{Y}_i(k) - Y_{C_i}(k)]^T\chi_i[\hat{Y}_i(k) - Y_{C_i}(k)] + \lambda_{ui}\Delta U_i(k)^T\Delta U_i(k) \quad (24)$$

With:

$$Y_{Ci} = [y_{C_i}(k+N_i+d_i)\cdots y_{Ci}(k+HP_i+d_i)] \quad (25)$$

The optimal control law is derived from analytical minimization of the previous cost function. Only the first control value is finally applied to the system.

$$u_i(k) = u_i(k-1) + m^T_{GPC_i}[Y_{Ci}(k) - \frac{\hat{G}(k)Y_i(k) + \hat{R}\Delta U_i(k-1)}{C_i(z^{-1})}] \quad (26)$$

Which: m^T_{GPCi} represents the first line of $(\hat{H}^T\chi_i\hat{H}+\lambda_{ui}I_{N_{Ci}})^{-1}\hat{H}^T$ and I_{N_C} is diagonal matrix of size $N_{Ci} * N_{Ci}$ and χ_i is diagonal matrix of size $HP_i * HP_i$

$$\chi_i = \begin{pmatrix}\lambda_{yi} & & 0\\ & \ddots & \\ 0 & & \lambda_{yi}\end{pmatrix} \; I_{N_{Ci}} = \begin{pmatrix}1 & & 0\\ & \ddots & \\ 0 & & 1\end{pmatrix} \quad (27)$$

For the systems with the constrains on the controller output value, on the controller increment output value or on the system output value, the vector Δu is calculated by function FMINCON of Optimization Toolbox of the language Matlab.

We can express constraint on the process in the form

$$\begin{aligned} u_{min} \le u_i(k) \le u_{max} \quad & \forall k\\ -\Delta u_s \le \Delta u_i(k) \le \Delta u_s \quad & \forall k\end{aligned} \quad (28)$$

D. Decoupling Control Design

The system design of GPC decoupling control based on ideal decoupler is presented in Fig. 6.

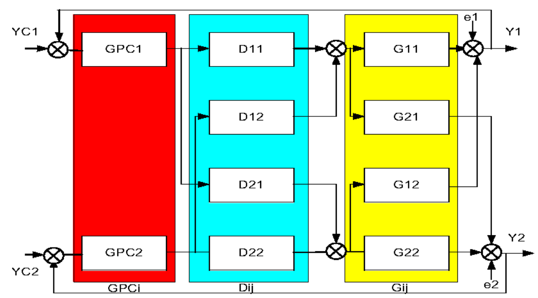

Figure 6. Configuration of GPC decoupling control system.

D11, D12, D21 and D22 are the decoupling compensation segment.

The advantage of using a decoupling controller over a multivariable GPC is that decoupling and tuning are separate tasks. The decoupling methods use usually in the multivariable coupled process includes diagonal matrix method, unit matrix method and feed-forward compensation method. In this work we interested to the diagonal matrix method to decouple the incubator system. In Fig. 6 G is dynamic transfer function and D is the decoupling matrix. To simplify decoupling process D11= D22=1.

The transfer functions are:

$$\begin{bmatrix}Y_1(k)\\ Y_2(k)\end{bmatrix} = \begin{bmatrix}G_{11}(z)+G_{12}(z).D_{21}(z) & G_{12}(z)+G_{11}(z).D_{12}(z)\\ G_{21}(z)+G_{22}(z).D_{21}(z) & G_{22}(z)+G_{21}(z).D_{12}(z)\end{bmatrix}\begin{bmatrix}U_1(k)\\ U_2(k)\end{bmatrix} \quad (29)$$

The decoupling conditions are obviously:

$$\begin{cases}G_{12}+G_{11}D_{12} = 0\\ G_{21}+G_{22}D_{21} = 0\end{cases} \quad (30)$$

The designed decoupling compensation in Fig. 6 is designed as:

$$\begin{cases} D_{11} = 1 \\ D_{22} = 1 \\ D_{21} = \dfrac{-G_{21}}{G_{22}} \\ D_{12} = \dfrac{-G_{12}}{G_{11}} \end{cases} \quad (31)$$

The decoupling dynamic transfer function is:

$$G_d(z) = \begin{bmatrix} \dfrac{G_{12}(z)}{G_{11}(z)} & 0 \\ 0 & \dfrac{G_{21}(z)}{G_{22}(z)} \end{bmatrix} \quad (32)$$

IV. SIMULATION RESULTS AND DISCUSSION

This section emphasises on examining the performance of the proposed DGPC for temperature and humidity control of a new born incubator system.

Before proceeding with the real time control, it is important to conduct computer simulation with Matlab software to check the feasibility of the proposed approach control. The principal parameters are set as follows; the prediction horizon is $HP_1 = HP_2 = 20$, the control horizon is $N_{C1} = N_{C2} = 1$, the weighting factors of the control increments are $\lambda_{u1} = 0.0026$, $\lambda_{u2} = 0.6273$ and the error weighting factor is $\lambda_{y1} = \lambda_{y2} = 1$. The coupling effect was suppressed by adding interaction compensators to controllers. In the following simulation plots the following ranges of the control signal applied to the heater and to the nebulizer were scaled to 0 to 100 %. The multivariable control was simulated with constraints and at sampling time T=20 seconds.

Chosen constraints $\begin{matrix} 0\% \le U_1 \le 100\% \\ 0\% \le U_2 \le 100\% \end{matrix}$

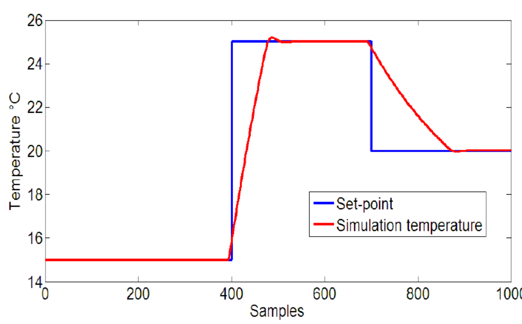

Figure 7. Simulation result of set-point tracking temperature for predictive decoupling control.

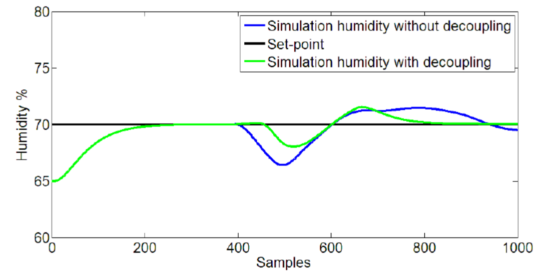

Figure 8. Simulation result of set-point tracking humidity for predictive control with and without decoupling.

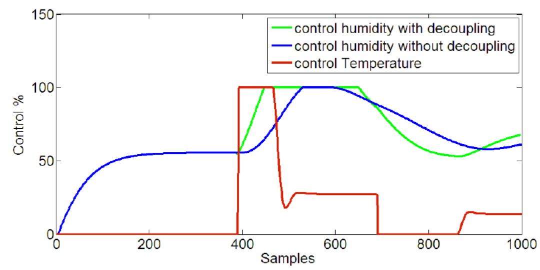

Figure 9. Simulation results of temperature and humidity control with and without decoupling in incubator system.

Described model has strong interaction between input U1 and output Y2, so the analyze has been done by changing temperature's reference and observing output signals of the humidity with and without decoupling. Figure 8 illustrates the simulation results using the decoupled GPC control. After stationary had been reached, mentioned reference increased from initial temperature to 25°C and decreases to 27°C that is seen in Fig. 7. In Fig. 8, comparing the simulation result of set-point tracking humidity for predictive control with and without decoupling, it can be noticed that there are great differences in the R.H (Relative Humidity) response due to the decoupling controller. However, simulation results obtained with Decoupling GPC, that take care of interactions in the system through compensation method improves the coupling effects. Fig. 9 illustrates the simulation results of temperature and humidity control with and without decoupling in incubator system.

V. CONCLUSION

In this paper, we have developed a multivariable control algorithm based on Decoupled Predictive control, which takes into account natural constraints on the actors (the heater and nebulizer). The proposed control algorithm, concern the temperature and humidity control of incubator. First we have designed a new active system which based on ultrasonic nebulizer and a real times parameter estimation method of TITO system is developed. Through the simulation results, the proposed method has been proved to be powerful under set-point changes and decoupling.

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