

# Notes on a Hierarchical Theory of Systems and Applications

by  
N. P. Karampetakis†, A. C. Pugh† and G.E. Hayton‡

† Department of Mathematical Sciences, Loughborough University of Technology, Loughborough, Leics LE11 3TU, England, U.K.

‡ Faculty of Information & Engineering Systems, Leeds Metropolitan University, Leeds, Calverley, Street, LS1 3HE, England, U.K.

**Abstract.** The main purpose of this paper is to give a physical interpretation of invariant zeros and indices in terms of the general zero-output behaviour of a linear dynamical system.

## 1. Introduction.

Linear time invariant multivariable systems may be considered as an interconnection of other subsystems, which may themselves be considered as an interconnection of other subsystems of lower order (Rosenbrock & Pugh 1974). Besides the definition of a hierarchical theory of systems, Rosenbrock & Pugh (1974) also considered some of the implications the transformation of strict system equivalence (Rosenbrock 1970) applied to the subsystems have on the subsystems higher up in the hierarchy. However in case where the impulsive behaviour of systems, is under consideration, then an extension of those known results seems to be necessary. The reason for this extension is the disadvantage of the transformation of strict system equivalence in that it preserves only the finite and not the infinite frequency behaviour of the system. One objective of this paper is then to extend the known results of Rosenbrock & Pugh (1974), so that the impulsive behaviour of the system and its subsystem is included. Another objective is to consider as an application of this theory the problem of reducing a general linear multivariable system to an equivalent generalised state space form.

## 2. Preliminary results.

Consider the set  $P(p, m)$  of  $(r+p) \times (r+m)$  polynomial matrices with  $r \geq \max(-p, -m)$ . A matrix transformation with many important systems theory implications is the following:

**Definition 1.** (Hayton et al. 1988) Let  $T_1(s), T_2(s) \in P(p, m)$ .  $T_1(s), T_2(s)$  are said to be *fully equivalent* (f.e.) if there exist polynomial matrices  $M(s), N(s)$  such that

$$\begin{pmatrix} M(s) & T_2(s) \end{pmatrix} \begin{pmatrix} T_1(s) \\ -N(s) \end{pmatrix} = 0 \quad (2.1)$$

where the compound matrices

$$\begin{pmatrix} M(s) & T_2(s) \end{pmatrix} ; \begin{pmatrix} T_1(s) \\ -N(s) \end{pmatrix} \quad (2.2)$$

satisfy the following:

- (i) they have full normal rank.
- (ii) they have no finite nor infinite zeros.
- (iii) the following McMillan degree conditions hold

$$\begin{aligned} \delta_M \begin{pmatrix} M(s) & T_2(s) \end{pmatrix} &= \delta_M \begin{pmatrix} T_2(s) \end{pmatrix} \\ \delta_M \begin{pmatrix} T_1(s) \\ -N(s) \end{pmatrix} &= \delta_M \begin{pmatrix} T_1(s) \end{pmatrix} \end{aligned} \quad (2.3)$$

A linear time invariant multivariable system  $\Sigma$  may be represented by an  $(r+p) \times (r+m)$  (with  $r > 0$ ) polynomial system matrix

$$P(s) = \begin{pmatrix} A(s) & B(s) \\ -C(s) & D(s) \end{pmatrix} \quad (2.4)$$

with  $\det[A(s)] \neq 0$  as has been described by Rosenbrock or by the *normalized form* of  $P(s)$

$$P(s) = \begin{pmatrix} T(s) & U \\ -V & 0 \end{pmatrix} = \begin{pmatrix} A(s) & B(s) & 0 & 0 \\ -C(s) & D(s) & I & 0 \\ 0 & -I & 0 & I \\ -\frac{1}{s} & -\frac{1}{s} & -\frac{1}{s} & -\frac{1}{s} \end{pmatrix} \quad (2.5)$$

as has been denoted by Verghese (1978). Let the set of all such matrices be denoted by  $\mathbf{P}(p, m)$ . Then we have

**Definition 2.** (Hayton et al. 1990)  $P_1(s), P_2(s) \in \mathbf{P}(p, m)$  are said to be *full system equivalent* (f.s.e.) if there exists polynomial matrices  $M(s), N(s), X(s), Y(s)$  such that

$$\begin{aligned} \begin{pmatrix} M(s) & 0 \\ X(s) & I \end{pmatrix} \underbrace{\begin{pmatrix} A_1(s) & B_1(s) \\ -C_1(s) & D_1(s) \end{pmatrix}}_{P_1(s)} &= \\ = \underbrace{\begin{pmatrix} A_2(s) & B_2(s) \\ -C_2(s) & D_2(s) \end{pmatrix}}_{P_2(s)} \begin{pmatrix} N(s) & Y(s) \\ 0 & I \end{pmatrix} & \quad (2.6) \end{aligned}$$

is a f.e. transformation.

Some results concerning the transformation of full system equivalence, which are indicative of its importance in the generalised study of linear systems behaviour, are included in the following

**Theorem 1.** (Walker 1988, Hayton et. al. 1990, Karampetakis & Vardoulakis 1993)

(i) Full system equivalence is an equivalence relation.

(ii) Under full system equivalence the following are invariant

(a) the generalised order  $f$  and the Rosenbrock degree  $d_r$ ,

(b) the transfer function and thus the finite and infinite transmission poles and zeros.

(c) the sets of finite system poles and zeros.

(d) the sets of finite and infinite decoupling zeros.

(e) the controllability and observability indices

(iii) Every system matrix  $P(s)$  is full system equivalent with a generalised state space system.

### 3. Hierarchical Theory of Systems and Full System Equivalence.

We shall start this section with a review of the philosophy of the hierarchical theory of systems. The hierarchical theory of systems views that every system  $\Sigma$  may be considered as the interconnection of other subsystems  $\Sigma_1, \Sigma_2, \dots, \Sigma_n$ . Every subsystem  $\Sigma_i$  may then be considered as the interconnection of other subsystems  $\Sigma_{i,1}, \Sigma_{i,2}, \dots, \Sigma_{i,n_i}$  of lower order.

Accordingly in this way we define an hierarchy of orders  $0, 1, 2, \dots, p$ ; the order 0 corresponds to the system  $\Sigma$  itself, the order 1 corresponds to the subsystems  $\Sigma_i$ , the order 2 corresponds to the subsystems  $\Sigma_{i,j}$  e.t.c.. The order  $q$  will be considered as the level of greatest subdivision of  $\Sigma$  and its elements are considered as the fundamental elements of  $\Sigma$ . In a certain sense the level of greatest subdivision can be considered as the level at which the system becomes decoupled.

The above scheme is more theoretic rather than practical and for these reasons we shall describe the results as they related to the form of matrices in our specific field of linear, time invariant, multivariable systems.

Consider therefore a system  $\Sigma$  which is formed by the interconnection of subsystems  $\Sigma_1, \Sigma_2, \dots, \Sigma_n$  which have the following form

$$A_i(\rho)\beta_i(t) = B_i(\rho)u_i(t) \quad i = 1, 2, \dots, n$$

$$y_i(t) = C_i(\rho)\beta_i(t) + D_i(\rho)u_i(t) \quad (3.1)$$

where  $A_i(\rho) \in \mathfrak{R}[\rho]^{r_i \times r_i}$ ,  $B_i(\rho) \in \mathfrak{R}[\rho]^{r_i \times m_i}$

,  $C_i(\rho) \in \mathfrak{R}[\rho]^{p_i \times r_i}$ ,  $D_i(\rho) \in \mathfrak{R}[\rho]^{p_i \times m_i}$

with corresponding system matrices :

$$P_i(s) = \begin{pmatrix} A_i(s) & B_i(s) \\ -C_i(s) & D_i(s) \end{pmatrix} \in \mathfrak{R}[s]^{(p_i+r_i) \times (m_i+r_i)} \quad (3.2)$$

The system  $\Sigma$  corresponds to the linear multivariable system

$$A(\rho)\beta(t) = B(\rho)u(t)$$

$$y(t) = C(\rho)\beta(t) + D(\rho)u(t) \quad (3.3)$$

where  $A(\rho) \in \mathfrak{R}[\rho]^{r \times r}$ ,  $B(\rho) \in \mathfrak{R}[\rho]^{r \times m}$ ,

$C(\rho) \in \mathfrak{R}[\rho]^{p \times r}$ ,  $D(\rho) \in \mathfrak{R}[\rho]^{p \times m}$  with

Rosenbrock system matrix :

$$P(s) = \begin{pmatrix} A(s) & B(s) \\ -C(s) & D(s) \end{pmatrix} \in \mathfrak{R}[s]^{(p+r) \times (m+r)} \quad (3.4)$$

We wish first to express  $P(s)$  explicitly in terms of the subsystems  $P_1(s), P_2(s), \dots, P_n(s)$  and their interconnections. The specific form of the interconnection equations we consider is

$$u_i(t) = - \sum_{j=1}^n F_{i,j} y_j(t) + K_i u(t)$$

$$y(t) = \sum_{i=1}^n L_i y_i(t) \quad (3.5)$$

with  $F_{i,j} \in \mathfrak{R}^{m_i \times p_j}$ ,  $K_i \in \mathfrak{R}^{m_i \times m}$

and  $L_i \in \mathfrak{R}^{p_i \times p_i}$  for  $i=1, 2, \dots, n$  and  $j=1, 2, \dots, n$ .

For this purpose, first define

$$\beta_S(t) = \left( \beta_1(t) \quad \dots \quad \beta_n(t) \right)^T \in \mathfrak{R}(t)^{\left( \sum_{i=1}^n r_i \right) \times 1}$$

$$u_S(t) = \left( u_1(t) \quad \dots \quad u_n(t) \right)^T \in \mathfrak{R}(t)^{\left( \sum_{i=1}^n m_i \right) \times 1}$$

$$y_S(t) = \left( y_1(t) \quad \dots \quad y_n(t) \right)^T \in \mathfrak{R}(t)^{\left( \sum_{i=1}^n p_i \right) \times 1}$$

$$A_S(s) = \text{block diag} \left( A_1(s) \quad \dots \quad A_n(s) \right)$$

$$B_S(s) = \text{block diag} \left( B_1(s) \quad \dots \quad B_n(s) \right)$$

$$C_S(s) = \text{block diag} \left( C_1(s) \quad \dots \quad C_n(s) \right)$$

$$D_S(s) = \text{block diag} \left( D_1(s) \quad \dots \quad D_n(s) \right)$$

$$F = \begin{pmatrix} F_{1,1} & F_{1,2} & \dots & F_{1,n} \\ F_{2,1} & F_{2,2} & \dots & F_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ F_{n,1} & F_{n,2} & \dots & F_{n,n} \end{pmatrix} \in \mathfrak{R}^{\bar{m} \times \bar{p}}$$

$$K = \begin{pmatrix} K_1^T & K_2^T & \dots & K_n^T \end{pmatrix}^T \in \mathfrak{R}^{\bar{m} \times m}$$

$$L = \begin{pmatrix} L_1 & L_2 & \dots & L_n \end{pmatrix} \in \mathfrak{R}^{p \times \bar{p}} \quad (3.6)$$

where  $\bar{m} = \sum_{i=1}^n m_i$ ,  $\bar{p} = \sum_{i=1}^n p_i$ . Then the equations of  $\Sigma_1, \Sigma_2, \dots, \Sigma_n$  can be written concisely in the form:

$$A_s(\rho)\beta_s(t) = B_s(\rho)u_s(t) \quad (3.7)$$

$$y_s(t) = C_s(\rho)\beta_s(t) + D_s(\rho)u_s(t)$$

which corresponds to the subsystem matrix

$$P_s(s) = \begin{pmatrix} A_s(s) & B_s(s) \\ -C_s(s) & D_s(s) \end{pmatrix} \quad (3.8)$$

In the same way the composite system equations for  $\Sigma_1, \Sigma_2, \dots, \Sigma_n$  interconnected as in (3.5) can be written as

$$\begin{pmatrix} A_s(s) & B_s(s) & 0 \\ -C_s(s) & D_s(s) & I \\ 0 & -I & F \end{pmatrix} \begin{pmatrix} \xi_s(t) \\ -u_s(t) \\ y_s(t) \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ K \end{pmatrix} u(t)$$

$$y(t) = \begin{pmatrix} 0 & 0 & L \end{pmatrix} \begin{pmatrix} \xi_s(t) \\ -u_s(t) \\ y_s(t) \end{pmatrix} \quad (3.9)$$

which corresponds to the system matrix

$$P_\Sigma(s) = \begin{pmatrix} A_s(s) & B_s(s) & 0 & 0 \\ -C_s(s) & D_s(s) & I & 0 \\ 0 & -I & F & K \\ -0 & -0 & -L & 0 \end{pmatrix} \quad (3.10)$$

under the assumption that

$$\det \begin{pmatrix} A_s(s) & B_s(s) & 0 \\ -C_s(s) & D_s(s) & I \\ 0 & -I & F \end{pmatrix} \neq 0 \quad (3.11)$$

It is important to know which properties of  $\Sigma$  remain invariant under transformations of a particular type applied to the subsystems  $\Sigma_i$ ,  $i=1,2,\dots,n$ . Rosenbrock & Pugh (1974) show that the finite pole/zero structures of  $\Sigma$  remains invariant under any strict system equivalence transformation of the subsystems  $\Sigma_i$ ,  $i=1,2,\dots,n$ . However some certain questions remain concerning the infinite pole/zero structures of  $\Sigma$ . Answers to these questions may be obtained as a consequence of the following

**Theorem 2.** Every invariant of  $\Sigma$  under full system equivalence is invariant under all transformations of full system equivalence applied to the systems  $\Sigma_i$ ,  $i=1,2,\dots,n$ .

**Proof.** Any system matrix  $P_i(s)$  which is full system equivalent to the system matrices  $P_i(s)$  can be written as

$$\begin{pmatrix} M_i(s) & 0 \\ X_i(s) & I \end{pmatrix} \underbrace{\begin{pmatrix} A_i(s) & B_i(s) \\ -C_i(s) & D_i(s) \end{pmatrix}}_{P_i(s)} =$$

$$= \underbrace{\begin{pmatrix} A_i(s) & B_i(s) \\ -C_i(s) & D_i(s) \end{pmatrix}}_{P_i(s)} \begin{pmatrix} N_i(s) & Y_i(s) \\ 0 & I \end{pmatrix} \quad (3.12)$$

where (3.12) is a full system equivalence transformation. Consequently any set of such transformations applied to  $P_1(s), P_2(s), \dots, P_n(s)$  can be represented by the full system equivalent transformations:

$$\begin{pmatrix} M(s) & 0 \\ X(s) & I \end{pmatrix} \underbrace{\begin{pmatrix} A_s(s) & B_s(s) \\ -C_s(s) & D_s(s) \end{pmatrix}}_{P_s(s)} =$$

$$= \underbrace{\begin{pmatrix} A_s(s) & B_s(s) \\ -C_s(s) & D_s(s) \end{pmatrix}}_{P_s(s)} \begin{pmatrix} N(s) & Y(s) \\ 0 & I \end{pmatrix} \quad (3.13)$$

where

$$M(s) = \text{block diag}(M_1(s), \dots, M_n(s))$$

$$N(s) = \text{block diag}(N_1(s), \dots, N_n(s)) \quad (3.14)$$

$$X(s) = \text{block diag}(X_1(s), \dots, X_n(s))$$

$$Y(s) = \text{block diag}(Y_1(s), \dots, Y_n(s))$$

On applying the interconnection defined previously, a composite system matrix  $P_\Sigma(s)$  is obtained from  $P_\Sigma(s)$  and it is readily confirmed that

$$\begin{pmatrix} M(s) & 0 & 0 & 0 \\ X(s) & I & 0 & 0 \\ 0 & 0 & I & 0 \\ 0 & 0 & 0 & I \end{pmatrix} P_\Sigma(s) =$$

$$= P_\Sigma(s) \begin{pmatrix} N(s) & Y(s) & 0 & 0 \\ 0 & I & 0 & 0 \\ 0 & 0 & I & 0 \\ 0 & 0 & 0 & I \end{pmatrix} \quad (3.15)$$

is a full system equivalence transformation since the relevant compound matrices of the above transformation are related via strict equivalence transformations to

$$\begin{pmatrix} M(s) & X(s) & 0 & 0 \\ 0 & I & 0 & 0 \\ A_S(s) & -C_S(s) & 0 & 0 \\ B_S(s) & D_S(s) & 0 & 0 \\ 0 & 0 & I & 0 \\ 0 & 0 & 0 & I \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}^T = \begin{pmatrix} I & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & I & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & I & 0 & 0 & 0 \\ 0 & 0 & I & 0 & 0 & I & 0 & 0 \\ 0 & 0 & I & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & I & 0 & 0 & 0 & 0 \\ 0 & -I & -F & L & 0 & 0 & I & 0 \\ 0 & 0 & -K & 0 & 0 & 0 & 0 & I \end{pmatrix}^T \times \begin{pmatrix} M(s) & X(s) & 0 & 0 \\ 0 & I & 0 & 0 \\ 0 & 0 & I & 0 \\ 0 & 0 & 0 & I \\ A_S(s) & -C_S(s) & 0 & 0 \\ B_S(s) & D_S(s) & -I & 0 \\ 0 & I & F & =L \\ 0 & 0 & K & 0 \end{pmatrix}^T \quad (3.16)$$

and

$$\begin{pmatrix} A_S(s) & B_S(s) & 0 & 0 \\ -C_S(s) & D_S(s) & 0 & 0 \\ -N(s) & -Y(s) & 0 & 0 \\ 0 & -I & 0 & 0 \\ 0 & 0 & I & 0 \\ 0 & 0 & 0 & I \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} I & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & I & 0 & 0 & 0 & 0 & I & 0 \\ 0 & 0 & 0 & 0 & I & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & I & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -I & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -I \\ 0 & 0 & I & 0 & 0 & -I & F & K \\ 0 & 0 & 0 & I & 0 & 0 & -L & 0 \end{pmatrix} \times$$

$$\begin{pmatrix} A_S(s) & B_S(s) & 0 & 0 \\ -C_S(s) & D_S(s) & I & 0 \\ 0 & -I & F & K \\ 0 & 0 & -L & 0 \\ -N(s) & -Y(s) & 0 & 0 \\ 0 & -I & 0 & 0 \\ 0 & 0 & -I & 0 \\ 0 & 0 & 0 & -I \end{pmatrix} \quad (3.17)$$

The above compound matrices are constructed from the compound matrices of the full equivalent transformation (3.13) via strict equivalence transformations and thus satisfy the conditions of full equivalence. Therefore the transformation (3.15) is a full system equivalence transformation, which verifies the theorem.

It thus follows that any operation of full system equivalence on the subsystems  $\Sigma_i$ ,  $i=1,2,\dots,n$  or equivalently to the system  $\Sigma_s$  corresponds to a transformation of full system equivalence on the composite system  $\Sigma$ . In the case where the matrices  $F$ ,  $K$  and  $L$  are not constant but polynomial (respectively proper) we observe that the compound matrices of the transformation (3.15) satisfy the conditions of full equivalence ( $C \cup \{\infty\}$ -equivalence) provided that (3.13) is a transformation of this type and therefore Theorem 1 remains the same.

This theorem shows that any property of  $\Sigma$  which is invariant under full system equivalence is unaffected by the particular choice of representation (within full system equivalence) of the subsystems  $\Sigma_i$ . Thus we can show the following

**Theorem 3.** Let a linear, time invariant, multivariable system  $\Sigma$  which comes from the interconnection of the linear, time invariant, multivariable systems  $\Sigma_i$ ,  $i=1,2,\dots,n$  (see (3.9)). Then there exists a generalized state space description  $\Sigma_r$  of  $\Sigma$  which is full system equivalent with the composite system  $\Sigma$ , and which is an interconnection of subsystems in generalised state space form.

**Proof.** Let  $\Sigma_i$  be a full system equivalent generalized state space system of  $\Sigma_i$  under the following full system equivalence transformation (Karampetakis & Vardulakis 1993):

$$\begin{pmatrix} M_i & 0 \\ 0 & I \end{pmatrix} \begin{pmatrix} A_i(s) & B_i(s) \\ -C_i(s) & D_i(s) \end{pmatrix} =$$

$$= \begin{pmatrix} sE_i - A_i & B_i \\ -C_i & 0 \end{pmatrix} \begin{pmatrix} N_i(s) & Y_i(s) \\ 0 & I \end{pmatrix} \quad (3.18)$$

Then, according to relation (3.15), we shall obtain the following full system equivalence transformation

$$\begin{pmatrix} M & 0 & 0 & 0 \\ 0 & I & 0 & 0 \\ 0 & 0 & I & 0 \\ 0 & 0 & 0 & I \end{pmatrix} P_{\Sigma}(s) = \begin{pmatrix} sE_s - A_s & B_s & 0 & 0 \\ -C_s & 0 & I & 0 \\ 0 & 0 & -I & F \\ 0 & 0 & -L & 0 \end{pmatrix} \begin{pmatrix} N(s) & Y(s) & 0 & 0 \\ 0 & I & 0 & 0 \\ 0 & 0 & -I & 0 \\ 0 & 0 & 0 & I \end{pmatrix} \quad (3.19)$$

where

$$sE_s - A_s = \text{block diag}(sE_1 - A_1, \dots, sE_n - A_n)$$

$$B_s = \text{block diag}(B_1, \dots, B_n)$$

$$C_s = \text{block diag}(C_1, \dots, C_n)$$

$$M = \text{block diag}(M_1, \dots, M_n)$$

$$N(s) = \text{block diag}(N_1(s), \dots, N_n(s))$$

$$Y(s) = \text{block diag}(Y_1(s), \dots, Y_n(s))$$

(3.20)

which verifies that the generalised state space description

$$\Sigma_r : \begin{pmatrix} \rho E_s - A_s & B_s & 0 \\ -C_s & 0 & I \\ 0 & -I & F \end{pmatrix} x(t) = \begin{pmatrix} 0 \\ 0 \\ K \end{pmatrix} u(t)$$

$$y(t) = \begin{pmatrix} 0 & 0 & L \end{pmatrix} x(t)$$

(3.21)

is full system equivalent to the system  $\Sigma$ .

**Theorem 4.** The linear, time invariant, multivariable system  $\Sigma$  which comes from the interconnection of the linear, time invariant, multivariable systems  $\Sigma_i$ ,  $i=1,2,\dots,n$  (see (3.9))

is full system equivalent to the generalised state space system

$$(\rho E_s - A_s + B_s F C_s) \dot{x}_s(t) = B_s K u(t) \quad (3.22)$$

$$y_s(t) = L C_s x_s(t)$$

**Proof.** It is easily seen that the transformation

$$\begin{pmatrix} I & -B_s F & B_s & 0 \\ 0 & -L & 0 & I \end{pmatrix} \begin{pmatrix} sE_s - A_s & B_s & 0 & 0 \\ -C_s & 0 & I & 0 \\ 0 & 0 & -I & F \\ 0 & 0 & -L & 0 \end{pmatrix} =$$

$$= \begin{pmatrix} sE_s - A_s + B_s F C_s & B_s K \\ -L C_s & -I \end{pmatrix} \begin{pmatrix} I & 0 & 0 & 0 \\ 0 & 0 & 0 & I \end{pmatrix} \quad (3.23)$$

is a full system equivalence transformation. From the full equivalent transformation (3.19) and the symmetry property of full system equivalence we finally obtain that the composite system  $\Sigma$  will be full system equivalent to the generalized state space system (3.22) which verifies the theorem.

#### Example 1.

Consider the following systems :

$$\Sigma_1 : (\rho^2 + 5\rho + 6)\beta_1(t) = (\rho + 1)u_1(t)$$

$$y_1(t) = (5 - 2\rho)\beta_1(t) + (3\rho + 2)u_1(t) \quad (E.1)$$

and

$$\Sigma_2 : \begin{pmatrix} \rho + 1 & \rho^2 \\ 0 & 1 \end{pmatrix} \underbrace{\begin{pmatrix} x_1(t) \\ x_2(t) \end{pmatrix}}_{\beta_2(t)} = \begin{pmatrix} \rho + 1 \\ 0 \end{pmatrix} u_2(t)$$

$$y_2(t) = \begin{pmatrix} 1 & 0 \end{pmatrix} \underbrace{\begin{pmatrix} x_1(t) \\ x_2(t) \end{pmatrix}}_{\beta_2(t)}$$

(E.2)

and takes the following equations of interconnection between  $\Sigma_1$  and  $\Sigma_2$  :

$$u_1(t) = -y_1(t) + y_2(t) + 2u(t)$$

$$u_2(t) = y_1(t) - u(t) \quad (E.3)$$

$$y(t) = y_1(t) - y_2(t)$$

Therefore we can define the matrices

$$F = \begin{pmatrix} 1 & -1 \\ -1 & 0 \end{pmatrix}; \quad K = \begin{pmatrix} 2 \\ -1 \end{pmatrix} \quad (E.4)$$

$$L = (1 \quad -1)$$

The Rosenbrock system matrix of the composite system  $\Sigma$  will have the following form :

$$P_{\Sigma}(s) = \begin{pmatrix} A_s(s) & B_s(s) & 0 & 0 \\ -C_s(s) & D_s(s) & I & 0 \\ 0 & -I & F & K \\ 0 & 0 & -L & 0 \end{pmatrix} = \begin{pmatrix} s^2 + 5s + 6 & 0 & 0 & s + 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & s + 1 & s^2 & 0 & s + 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 2s - 5 & 0 & 0 & 3s + 2 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & 1 & -1 & 2 \\ 0 & 0 & 0 & 0 & -1 & -1 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 0 & -1 & -1 & 1 & 0 \end{pmatrix} \quad (E.5)$$

Consider also the full system equivalent generalized state space systems  $\Sigma_{R_1}$  and  $\Sigma_{R_2}$  (see Bosgra & Van Der weiden (1981), Karampetakis & Vardulakis (1993)) of  $\Sigma_1$  and  $\Sigma_2$  respectively:

$$\Sigma_{R_1} = \begin{pmatrix} 5s+6 & s+1 & -s & 0 & 0 \\ 2s-5 & 3s+2 & 0 & 1 & 0 \\ s & 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 & 1 \\ 0 & 0 & 0 & -1 & 0 \end{pmatrix} \quad (E.6)$$

and

$$\Sigma_{R_2} = \begin{pmatrix} s+1 & 0 & s+1 & -s & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 1 & 0 \\ 0 & s & 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & -1 & 0 \end{pmatrix} \quad (E.7)$$

Then the full system equivalent generalized state space system of the composite system (E.5) will be the following:

$$\begin{aligned} (\rho E_s - A_s + B_s F C_s) \xi_s(t) &= B_s K u(t) \\ y_s(t) &= L C_s \xi_s(t) \end{aligned} \quad (E.8)$$

where

$$\begin{aligned} \rho E_s - A_s + B_s F C_s &= \\ &= \begin{pmatrix} 5s+6 & s+1 & -s & 0 & 0 & 0 & 0 & 0 & 0 \\ 2s-5 & 3s+2 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ s & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & s+1 & 0 & s+1 & -s & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & s & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 & -1 & 0 & 0 \end{pmatrix} \end{aligned} \quad (E.9)$$

$$B_s K = (0 \ 0 \ 0 \ 2 \ 0 \ 0 \ 0 \ 0 \ -1)^T \quad (E.10)$$

$$L C_s = (0 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 0 \ -1) \quad (E.11)$$

#### 4. An Application of the Hierarchical Theory of Systems.

A direct implication of Theorem 3 concerns the reduction of a general polynomial description to a full system equivalent generalized state space form. More specifically, consider the polynomial matrix description:

$$\begin{aligned} \Sigma: A(\rho)\beta(t) &= B(\rho)u(t) \\ y(t) &= C(\rho)\beta(t) + D(\rho)u(t) \end{aligned} \quad (4.1)$$

and let its *normalized form* (Verghese 1978) be the following:

$$\begin{aligned} \Sigma: \underbrace{\begin{pmatrix} A(\rho) & B(\rho) & 0 \\ -C(\rho) & D(\rho) & I \\ 0 & -I & 0 \end{pmatrix}}_{T(\rho)} \underbrace{\begin{pmatrix} \beta(t) \\ -u(t) \\ y(t) \end{pmatrix}}_{\xi(t)} &= \underbrace{\begin{pmatrix} 0 \\ 0 \\ I \end{pmatrix}}_U u(t) \\ y(t) &= \underbrace{\begin{pmatrix} 0 & 0 & I \end{pmatrix}}_V \underbrace{\begin{pmatrix} \beta(t) \\ -u(t) \\ y(t) \end{pmatrix}}_{\xi(t)} \end{aligned} \quad (4.2)$$

Then we have the following:

**Theorem 5.** Let  $(C, sE-A, B)$  be a strongly irreducible realization of  $T(s)^{-1}$ . Then the generalized state space system:

$$\dot{S}: E\dot{x}(t) = Ax(t) + BUu(t) \quad (4.3)$$

$$y(t) = VCx(t)$$

is full system equivalent to the system  $\Sigma$  of the form (4.1)-(4.2).

**Proof.** It is easily seen that  $\Sigma$  is an interconnection of the following three systems:

$$\begin{aligned} \Sigma_1: I\beta_1(t) &= Uu_1(t) \\ y_1(t) &= I\beta_1(t) \end{aligned} \quad (4.4a)$$

$$\begin{aligned} \Sigma_2: T(\rho)\beta_2(t) &= Iu_2(t) \\ y_2(t) &= I\beta_2(t) \end{aligned} \quad (4.4b)$$

$$\begin{aligned} \Sigma_3: I\beta_3(t) &= Iu_3(t) \\ y_3(t) &= V\beta_3(t) \end{aligned} \quad (4.4c)$$

under the following interconnections:

$$\begin{aligned} \begin{pmatrix} u_1(t) \\ u_2(t) \\ u_3(t) \end{pmatrix} &= \underbrace{\begin{pmatrix} 0 & 0 & 0 \\ -I & 0 & 0 \\ 0 & -I & 0 \end{pmatrix}}_F \begin{pmatrix} y_1(t) \\ y_2(t) \\ y_3(t) \end{pmatrix} + \underbrace{\begin{pmatrix} I \\ 0 \\ 0 \end{pmatrix}}_K u(t) \\ y(t) &= \underbrace{\begin{pmatrix} 0 & 0 & I \end{pmatrix}}_L \begin{pmatrix} y_1(t) \\ y_2(t) \\ y_3(t) \end{pmatrix} \end{aligned} \quad (4.5)$$

$\Sigma_2$  is strongly irreducible (has no finite nor infinite decoupling zeros) and thus any generalized state space realization of its transfer function i.e.  $T(s)^{-1}$ , will be full system equivalent to this system (Karampetakis & Vardulakis 1992). Thus according to our initial assumption that  $(C,$

$sE-A, B$  be a strongly irreducible realization of  $T(s)^{-1}$  then  $S_2$ :

$$S_2: \begin{aligned} E\dot{x}(t) &= Ax(t) + Bu_2(t) \\ y_2(t) &= Cx_2(t) \end{aligned} \quad (4.6)$$

is full system equivalent to the system  $\Sigma_2$ . Then according to Theorem 4, the full system equivalent generalized state space system  $S$  of the interconnected system  $\Sigma$  will be the following:

$$S: \begin{aligned} (\rho E_S - A_S + B_S FC_S)\xi_S(t) &= B_S Ku(t) \\ y(t) &= LC_S \xi_S(t) \end{aligned} \quad (4.7)$$

where

$$sE_S - A_S = \begin{pmatrix} I & 0 & 0 \\ 0 & sE - A & 0 \\ 0 & 0 & I \end{pmatrix} \quad (4.8)$$

$$B_S = \begin{pmatrix} U & 0 & 0 \\ 0 & B & 0 \\ 0 & 0 & I \end{pmatrix}; \quad C_S = \begin{pmatrix} I & 0 & 0 \\ 0 & C & 0 \\ 0 & 0 & V \end{pmatrix}$$

Thus

$$sE_S - A_S + B_S FC_S = \begin{pmatrix} I & 0 & 0 \\ -B & sE - A & 0 \\ 0 & -C & I \end{pmatrix}$$

$$B_S K = \begin{pmatrix} U^T & 0 & 0 \end{pmatrix}^T \quad (4.9)$$

$$LC_S = \begin{pmatrix} 0 & 0 & V \end{pmatrix}$$

and therefore the Rosenbrock system matrix of  $S$  will be

$$P_S(s) = \begin{pmatrix} I & 0 & 0 & U \\ -B & sE - A & 0 & 0 \\ 0 & -C & I & 0 \\ 0 & 0 & -V & 0 \end{pmatrix} \quad (4.10)$$

Note also that the following transformation:

$$\begin{pmatrix} B & I & 0 & 0 \\ 0 & 0 & V & I \end{pmatrix} \begin{pmatrix} I & 0 & 0 & U \\ -B & sE - A & 0 & 0 \\ 0 & -C & I & 0 \\ 0 & 0 & -V & 0 \end{pmatrix} = \begin{pmatrix} sE - A & BU \\ -VC & 0 \end{pmatrix} \begin{pmatrix} 0 & I & 0 & 0 \\ 0 & 0 & 0 & I \end{pmatrix} \quad (4.11)$$

is obviously a full system equivalence (more precisely a complete system equivalence) transformation. Thus the system:

$$S: \begin{aligned} E\dot{x}(t) &= Ax(t) + BUu(t) \\ y(t) &= VCx(t) \end{aligned} \quad (4.12)$$

is a full system equivalent generalized state space model of  $\Sigma$  due to the transitivity property of full system equivalence. It is known however (Karampetakis et. al. 1994) that the full system equivalence transformation

which relate the systems  $\Sigma$  and  $S'$  is the following:

$$\begin{pmatrix} T(s)C(sE-A)^{-1} & 0 \\ 0 & I \end{pmatrix} \begin{pmatrix} sE-A & BU \\ -VC & 0 \end{pmatrix} = \begin{pmatrix} T(s) & U \\ -V & 0 \end{pmatrix} \begin{pmatrix} C & 0 \\ 0 & I \end{pmatrix} \quad (4.13)$$

An implementation of the above construction method may be found in the generalized state space reduction models presented by Vardulakis (1991) and in the extension of Tan & VanDewalles's realization method presented by Karampetakis et. al. (1994).

**Example 2.** Consider a system  $\Sigma$  described by the following equations:

$$\Sigma: (\rho^2 + 5\rho + 6)\beta(t) = (\rho + 1)u(t) \quad (E.1)$$

$$y(t) = (5 - 2\rho)\beta(t) + (3\rho + 2)u(t)$$

or its normalized form (Verghese 1978):

$$\underbrace{\begin{pmatrix} \rho^2 + 5\rho + 6 & \rho + 1 & 0 \\ 2\rho - 5 & 3\rho + 2 & 1 \\ 0 & -1 & 0 \end{pmatrix}}_{T(\rho)} \underbrace{\begin{pmatrix} \beta(t) \\ -u(t) \\ y(t) \end{pmatrix}}_{\xi(t)} = \underbrace{\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}}_U u(t)$$

$$y(t) = \underbrace{\begin{pmatrix} 0 & 0 & 1 \end{pmatrix}}_V \xi(t) \quad (E.2)$$

It is easily shown that:

$$T(s)^{-1} = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 9 & 11 & 3 & -3 \end{pmatrix} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}}_C$$

$$\times \underbrace{\begin{pmatrix} s+2 & 0 & 0 & 0 \\ 0 & s+3 & 0 & 0 \\ 0 & 0 & 1 & -s \\ 0 & 0 & 0 & 1 \end{pmatrix}}_{sE-A}^{-1} \underbrace{\begin{pmatrix} 1 & 0 & -1 \\ -1 & 0 & 1 \\ 0 & 1/3 & 1 \\ 0 & 0 & 1 \end{pmatrix}}_B \quad (E.3)$$

where  $\{C, sE-A, B\}$  is a strongly irreducible realization. Then according to Theorem 4 the system:

$$S: \underbrace{\begin{pmatrix} \rho+2 & 0 & 0 & 0 \\ 0 & \rho+3 & 0 & 0 \\ 0 & 0 & 1 & -\rho \\ 0 & 0 & 0 & 1 \end{pmatrix}}_{\rho E-A} \underbrace{\begin{pmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \end{pmatrix}}_{x(t)} = \underbrace{\begin{pmatrix} -1 \\ 2 \\ 1 \\ 1 \end{pmatrix}}_{BU} u(t)$$

$$y(t) = \underbrace{\begin{pmatrix} 9 & 11 & 3 & -3 \end{pmatrix}}_{VC} x(t) \quad (E.4)$$

is full system equivalent to the system  $\Sigma$ .

## 5. Conclusions.

This paper presents a discussion of the role of full system equivalence transformation within the hierarchical theory of systems. More specifically we prove (Theorem 2) that every property of a linear multivariable system  $\Sigma$  which remains invariant under the transformation of full system equivalence, is unaffected by the particular choice (within full system equivalence) of the subsystems  $\Sigma_i$ ,  $i=1,2,\dots,n$  of  $\Sigma$ . As a result of this conclusion we have derived a reduction algorithm which has the property to reduce any composite linear multivariable system  $\Sigma$  to a full system equivalent generalized state space form.

## REFERENCES

- [1] Bosgra O.H. and Van Der Weiden A.J.J., 1981, Realizations in generalized state-space form for polynomial system matrices and the definition of poles, zeros and decoupling zeros at infinity., *Int. J. Control*, 33, 393-411.
- [2] Hayton G.E., Pugh A.C. and Fretwell P., 1988, Infinite elementary divisors of a matrix polynomial and implications., *Int. J. Control*, 47, 53-64.
- [3] Hayton G.E., Walker A.B. and Pugh A.C., 1990, Infinite frequency structure-preserving transformations for general polynomial system matrices., *Int. J. Control*, 52, 1-14.
- [4] Karampetakis N. P. and Vardulakis A.I.G., 1993, Generalized state space system matrix equivalents of a Rosenbrock system matrix., *IMA Journal of Control and its Information*, 10, 323-344.
- [5] Karampetakis N.P., Pugh A.C., Vardulakis A.I. and Hayton G.E., 1994, Generalized state space representations for linear multivariable systems., *Proceedings of the IEEE Mediterranean Symposium on New Directions in Control Theory and Applications*, pp.209-216, Chania, Crete, Greece, June 19-22, 1994.
- [6] Rosenbrock H.H., 1970, *State Space and Multivariable Theory*, Nelson, London.
- [7] Rosenbrock H.H. and Pugh A.C., 1974, Contributions to a hierarchical theory of systems., *Int. J. Control*, 19, 845-867.
- [8] Vardulakis A.I.G., 1991, On the transformation of a polynomial matrix model of a linear multivariable system to generalized state space form., *Proceedings of the 30th IEEE Conference on Decision and Control*, December 11-13, 1991, Brighton, England.
- [9] Verghese G.C., 1978, *Infinite-frequency Behaviour in Generalized Dynamical Systems*, Ph.D. Dissertation, Stanford University, Stanford, C.A.