Industrial Automation

(Automação de Processos Industriais)

Supervised Control of Discrete Event Systems

http://www.isr.ist.utl.pt/~pjcro/courses/api0910/api0910.html

Prof. Paulo Jorge Oliveira
pjcro @ isr.ist.utl.pt
Tel: 21 8418053 or 2053 (internal)

Syllabus:

...

Chap. 8 - SEDs and Industrial Automation [2 weeks]

Chap. 9 – Supervised Control of SEDs [1 semana]

*** SCADA**

*** Methodologies for the Synthesis of Supervision Controllers**

*** Failure detection**

Some jokes available in http://members.iinet.net.au/~ianw/cartoon.html

The End.

Some pointers on Supervised Control of DES

History:

The SCADA Web, http://members.iinet.net.au/~ianw/
Monitoring and Control of Discrete Event Systems
Stéphane Lafortune,
http://www.ece.northwestern.edu/~ahaddad/ifac96/introductory_workshops.html

Tutorial:

http://vita.bu.edu/cgc/MIDEDS/
http://www.daimi.au.dk/PetriNets/

Analysers, and Simulators:

http://www.nd.edu/~isis/techreports/isis-2002-003.pdf (Users Manual)
http://www.nd.edu/~isis/techreports/spnbox/ (Software)

Bibliography:

* Livros de SCADA http://www.sss-mag.com/scada.html
* Moody J. e Antsaklis P., “Supervisory Control of Discrete Event Systems using Petri Nets,” Kluwer Academic Publishers, 1998.
* Cassandras, Christos G., "Discrete Event Systems - Modeling and Performance Analysis," Aksen Associates, 1993.
* Yamalidou K., Moody J., Lemmon M. and Antsaklis P. Feedback Control of Petri Nets Based on Place Invariants http://www.nd.edu/~lemmon/isis-94-002.pdf

Supervision of DES

Supervisory

Control

And

Data

Acquisition

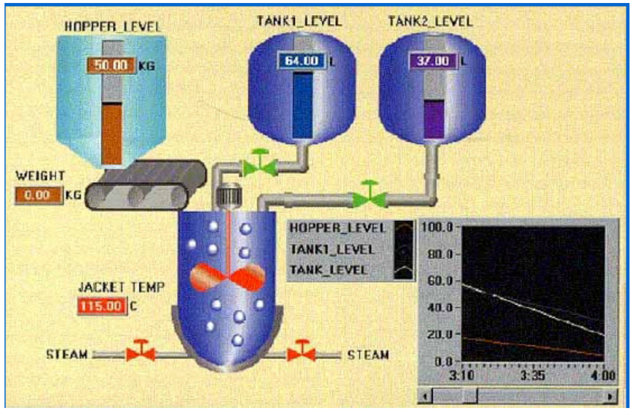
Supervision of DES

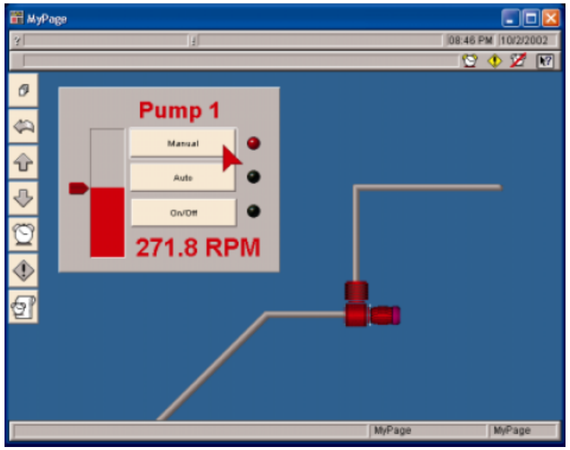
SCADA topics

- Remote monitoring of the state of automation systems
- Logging capacity (resorting to specialized Databases)
- Able to access to *historical* information (plots along time, with selectable periodicity)
- Advanced tools to design Human-Machine interfaces
- Faillure Detection and Isolation capacity (*treshold* and/or logocal functions) on supervised quantities
- Access control

Supervision of DES

Examples of SCADA





API

P. Oliveira

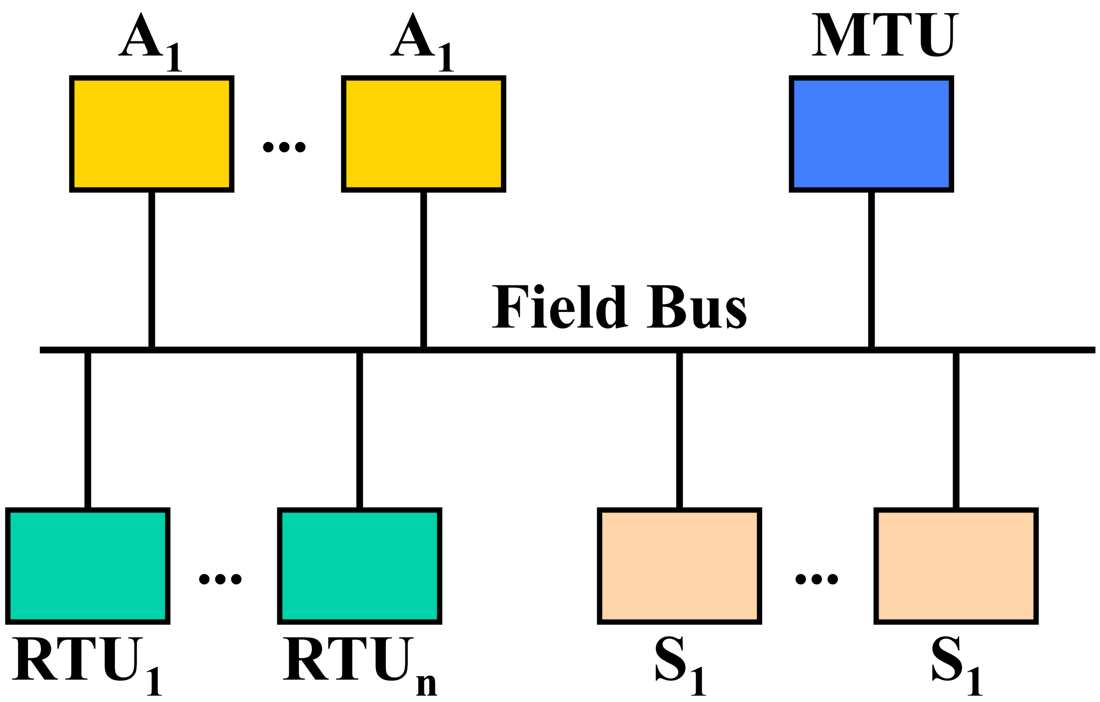
Supervision of DES

Examples of software packages including SCADA solutions

- **Aimax**, de Desin Instruments S.A.
- **CUBE**, Orsi España S.A.
- **FIX**, de Intellution.
- **Lookout,** National Instruments.
- **Monitor Pro,** de Schneider Electric.
- **SCADA InTouch**, de LOGITEK.
- **SYSMAC SCS**, de Omron.
- **Scatt Graph 5000,** de ABB.
- **WinCC**, de Siemens.

Supervision of DES

Hardware Support Achitecture of SCADA



Legend:

MTU - Main Terminal Unit

RTU - Remote Term. Unit

S – Sensor

A - Actuator

Supervision of DES

And

Now

Something

Completly

Different

Supervision of DES

Objectives of the Supervised Control

- Supervise and bound the work of the supervised DES
- Reinforce that some propeties are verified
- Assure that some states are not reached
- Performance criteria are verified
- Prevent the deadlock od DES
- Constrain on the use of ressources (e.g. mutual exclusion)

Supervision of DES

Some history on Supervised Control

- Methods for finite automata [Ramadge et *al.*], 1989
  - some are based on brute-force search (!)
  - or may require simulation (!)

- Formal verification of *software* in Computer Science (since the 60s) and on *hardware* (90, ...)

- Supervisory Control Method of Petri Nets, method based on *monitors* [Giua et *al.*], 1992.

- Supervisory Control of Petri Nets based on Place Invariants [Moody, Antsaklis et *al.*], 1994 (shares some similitude with the previous one, but deduced independently!...).

Supervision of DES

Advantagens of the Supervisory Control of Petri Nets

- Mathematical representation is clear (and easy)
- Resorts only to linear algebra (matrices)
- More compact then automata
- Straithforward the representation of infinity state spaces
- Intuitive graphical representation available

The representation of the controller as a Petri Net leads to simplified Analysis and Synthesis tasks

Supervision of DES

Method of the Place Invariants [ISIS docs]:

What type of relations can be represented in the method of Place Invariants?

• Sets of linear constraints in the state space

• Representation of convex regions (there are extentions for non-convex regions) (?...)

• Constraints to guarantee liveness and to avoid deadlocks (that can be expressed, in general, as linear constraints)

• Constraints on the events and timmings (bis)

Supervision of DES

Advantages of the Method of the Place Invariants [ISIS docs]:

Other characteristics that can impact on the solutions?

• Existence and uniqueness

• Optimality of the solutions (e.g. see maximal permissivity next)

• Existence of transition non-controllable and/or not observable (remind definitions for time-driven systems)

In general the solutions can be found solving:

Linear Programming Problems, with Linear Constraints

Methods of Analysis/Synthesis

Method of the Matrix Equations (just to remind)

The dynamics of the Petri net state can be written in compact form as:

$$\mu(k+1) = \mu(k) + Dq(k)$$

where:

- $\mu(k+1)$ - marking to be reached
- $\mu(k)$ - initial marking
- $q(k)$ - firing vector (transitions)
- D - incidence matrix. Accounts the balance of tokens, giving the transitions fired.

Methods of Analysis/Synthesis

How to build the Incidence Matrix?

For a Petri net with *n* places and *m* transitions

$$\mu \in N_0^{\ n}$$

$$q \in N_0^{\ m}$$

$$D = D^+ - D^- \qquad \in \mathrm{Z}^{n\times m}$$

The enabling firing rule is $\mu \geq D^- q$.

Can also be writen in compact form as the inequality

$$\mu + Dq \geq 0,$$

interpreted element by element.

Methods of Synthesis

Some notation for the method

- The supervised system is modelled as a Petri net with n places and m transitions, and incidence matrix

$$D_P \in Z^{n \times m}.$$

- The supervisor is modelled as a Petri net with n_C places and m transitions, and incidence matrix

$$D_C \in Z^{n_C \times m}.$$

- The resulting total system has an incidence matrix

$$D \in Z^{(n+n_C) \times m}.$$

Methods of Synthesis

Theorem: **(1)**

Synthesis of Controllers based on Place Invariants

Given the set of linear state constraints that the supervised system must follow, writte as

$$L\mu_P \leq b, \quad \mu_P \in N_0^{\ n}, \quad L \in Z^{n_C \times n} \quad and \quad b \in Z^{n_C}.$$

If $b - L\mu_{P_0} \geq 0$, then the controller with incedence matrix and initial marking, respectively

$$D_C = -LD_P, \quad \text{and} \quad \mu_{C_0} = b - L\mu_{P_0},$$

makes the constraints be verified for all markings obtained from the initial marking.

Methods of Synthesis

Theorem:

Proof outline:

The constraint $L\mu_P \leq b$ can be written as

$L\mu_P + \mu_C = b$, using the slack variables μ_C.

They represent the marking of the n_C places of the controller.

To have a place invariant, the relation $x^T D = 0$ must be verified and in particular, given the previous constraint:

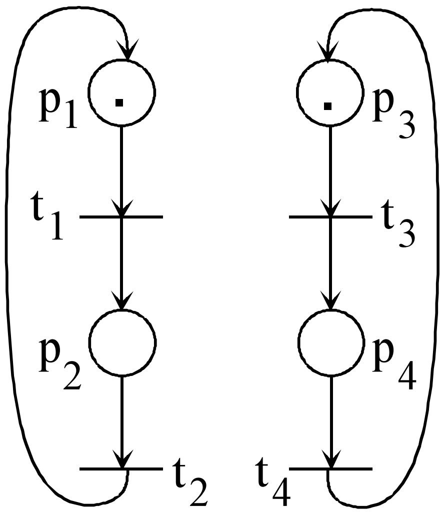
$$x^T D = \begin{bmatrix} L & I \end{bmatrix} \begin{bmatrix} D_P \\ D_C \end{bmatrix} = 0, \text{ resulting } \boxed{D_C = -LD_P.}$$

From $L\mu_{P_0} + \mu_{C_0} = b$, follows that $\boxed{\mu_{C_0} = b - L\mu_{P_0}.}$ ∎

Methods of Synthesis

Example of controller synthesis

Mutual Exclusion



Linear constraint: $\mu_2 + \mu_4 \leq 1$

That can be written as:

$$L\mu_P \leq b \qquad \begin{bmatrix} 0 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} \mu_1 \\ \mu_2 \\ \mu_3 \\ \mu_4 \end{bmatrix} \leq 1.$$

Incidence Matrix

$$D_P = \begin{bmatrix} -1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & -1 \end{bmatrix}$$

and initial marking

$$\mu_{P_0} = \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix}.$$

Methods of Synthesis

Example of controller synthesis

Mutual Exclusion

1) Test

$$b - L\mu_{P_0} = 1 - \begin{bmatrix} 0 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix} = 1 \geq 0.$$

OK.

2) Compute

$$D_C = -LD_P = -\begin{bmatrix} 0 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} -1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & -1 \end{bmatrix} = \begin{bmatrix} -1 & 1 & -1 & 1 \end{bmatrix},$$

and

$$\mu_{C_0} = b - L\mu_{P_0} = 1.$$

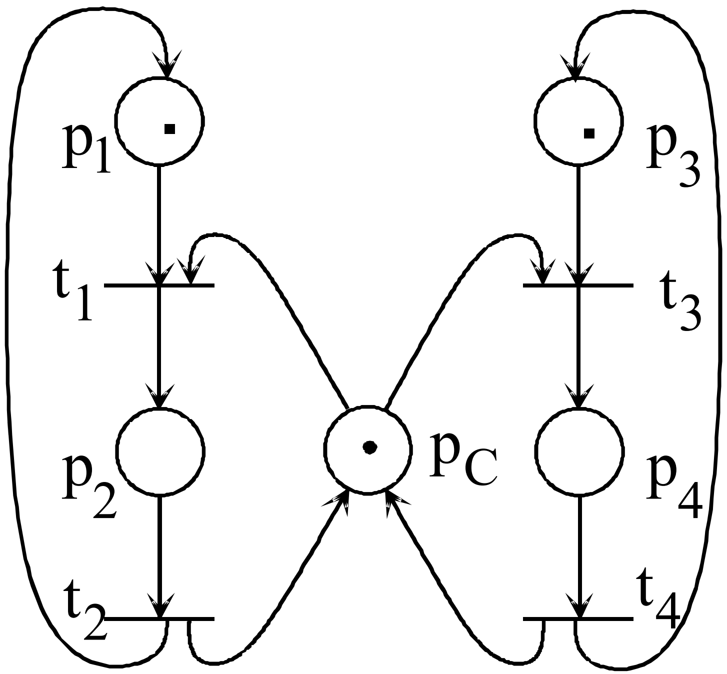
OK.

Methods of Synthesis

Example of controller synthesis

Mutual Exclusion

3) Resulting in



$$D = \begin{bmatrix} -1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & -1 \\ -1 & 1 & -1 & 1 \end{bmatrix}$$

$$\mu_0 = \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \\ 1 \end{bmatrix}$$

OK.
UAU!!!.

Methods of Synthesis

Definition:

Maximal permissivity occurs when all the linear constraints are verified and all legal markings can be reached.

Lemmas:

i) The controllers obtained in (1) have maximal permissivity.

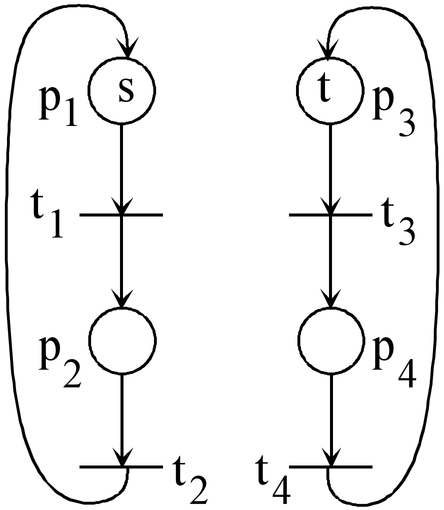
ii) Given the linear constraints used, the place invariants obtained with the controller synthesized with (1) are the same as the invariants associated with the initial system.

Methods of Synthesis

Example of controller synthesis

$\forall s \in N_0, \forall t \in N_0, \forall n \in N_0$

Readers / Writers



Linear constraints for n books: $\mu_2 + n\mu_4 \le n$

That can be written as:

$$L\mu_P \le b \qquad \begin{bmatrix} 0 & 1 & 0 & n \end{bmatrix} \begin{bmatrix} \mu_1 \\ \mu_2 \\ \mu_3 \\ \mu_4 \end{bmatrix} \le n.$$

Incidence Matrix

$$D_P = \begin{bmatrix} -1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & -1 \end{bmatrix}$$

and initial marking

$$\mu_{P_0} = \begin{bmatrix} s \\ 0 \\ t \\ 0 \end{bmatrix}.$$

Methods of Synthesis

Example of controller synthesis

Readers / Writers

1) Test

$$b - L\mu_{P_0} = n - \begin{bmatrix} 0 & 1 & 0 & n \end{bmatrix} \begin{bmatrix} s \\ 0 \\ t \\ 0 \end{bmatrix} = n \geq 0.$$

OK.

2) Compute

$$D_C = -LD_P = -\begin{bmatrix} 0 & 1 & 0 & n \end{bmatrix} \begin{bmatrix} -1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & -1 \end{bmatrix} = \begin{bmatrix} -1 & 1 & -n & n \end{bmatrix},$$

and

$$\mu_{C_0} = b - L\mu_{P_0} = n.$$

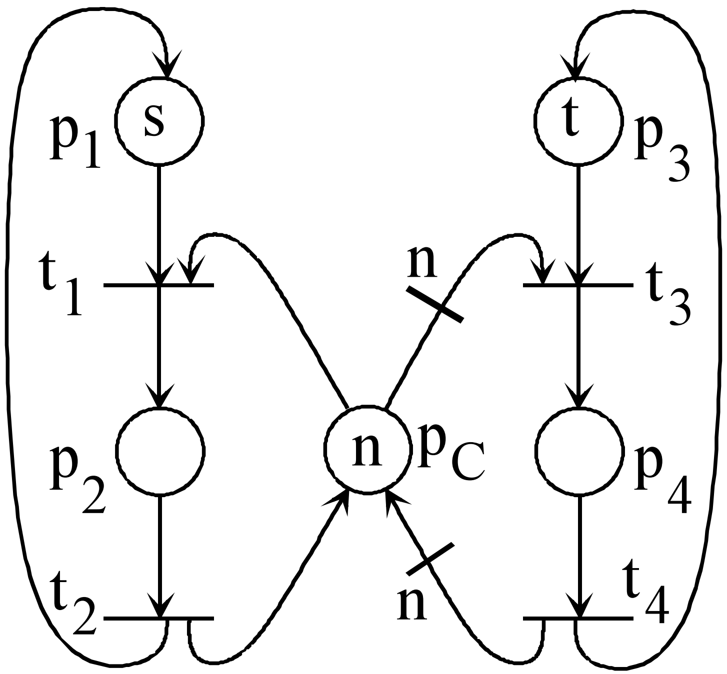
OK.

Methods of Synthesis

Example of controller synthesis

Readers / Writers

3) Resulting in



$$D = \begin{bmatrix} -1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & -1 \\ -1 & 1 & -n & n \end{bmatrix}$$

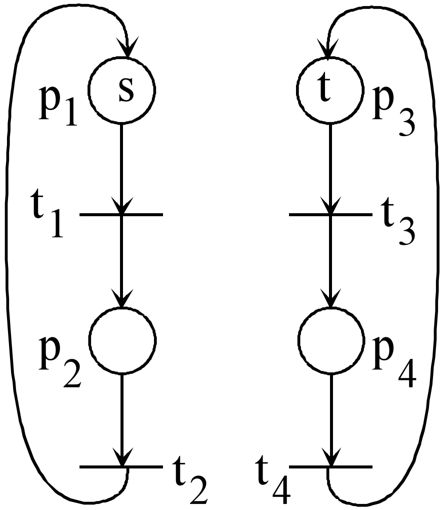
$$\mu_0 = \begin{bmatrix} s \\ 0 \\ t \\ 0 \\ n \end{bmatrix}$$

OK.
UAU!!!.

Methods of Synthesis

Example of controller synthesis

Producer / Consumer



Incidence matrix

$$D_P = \begin{bmatrix} -1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & -1 \end{bmatrix}$$

Initial marking

$$\mu_{P_0} = \begin{bmatrix} s \\ 0 \\ t \\ 0 \end{bmatrix}.$$

What is the linear constraint?

Not possible to write it as a linear constraint $L\mu_P \leq b$!

Is it impossible to solve this problem with the proposed method?

Methods of Synthesis

Generalized linear constraint

Let the generalized linear constraint be

$$L\mu_P + Fq_P + Cv_P \leq b,$$
$$\mu_P \in N_0^{\ n}, v_P \in N_0^{\ m}, q_P \in N_0^{\ m},$$
$$L \in Z^{n_C \times n}, F \in Z^{n_C \times m}, C \in Z^{n_C \times m}, e \quad b \in Z^{n_C},$$

where

* μ_P is the marking vector for system P;
* q_P is the firing vector since t_0;
* v_P is the number of transtitions (firing) that can occur, also designated as Parikh vector.

Methods of Synthesis

Function LINENF of SPNBOX

Theorem: Synthesis of Controllers based on Place Invariants, for Generalized Linear Contraints

Given the generalized linear constraint $L\mu_P + Fq_P + Cv_P \leq b,$

if $b - L\mu_{P_0} \geq 0,$ then the controller with incidence matrix and initial marking, respectively

$$D_C^- = \max\left(0, LD_P + C, F\right)$$
$$D_C^+ = \max\left(0, F - \max\left(0, LD_P + C\right)\right) - \min\left(0, LD_P + C\right),$$

$$\mu_{C_0} = b - L\mu_{P_0} - Cv_{P0},$$

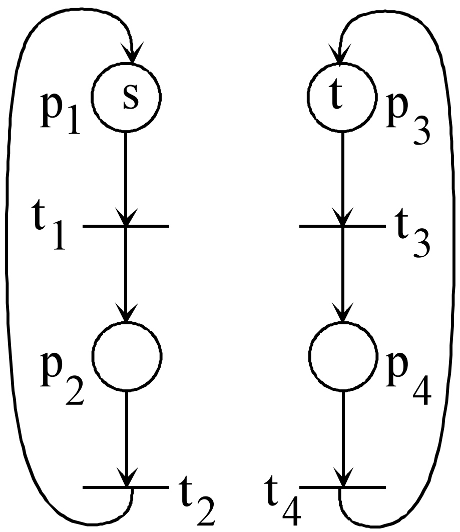
guarantees that constraints are verified for the states resulting from the initial marking.

Methods of Synthesis

Example of controller synthesis

$\forall s \in N_0, \forall t \in N_0, \forall n \in N_0$

Producer / Consumer



Linear constraint: $v_3 \le v_2$

That can be written as:

$$Cv_P \le b$$

$$L = 0, F = 0$$

$$\begin{bmatrix} 0 & -1 & 1 & 0 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} \le 0.$$

Incidence matrix

$$D_P = \begin{bmatrix} -1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & -1 \end{bmatrix}$$

Initial marking

$$\mu_{P_0} = \begin{bmatrix} s \\ 0 \\ t \\ 0 \end{bmatrix}.$$

Methods of Synthesis

Example of controller synthesis

Producer / Consumer

1) Test

$$b - L\mu_{P_0} = 0 - 0 \geq 0.$$

OK.

2) Compute

$$D_C^- = \max\left(0, \begin{bmatrix}0 & -1 & 1 & 0\end{bmatrix}, 0\right) = \begin{bmatrix}0 & 0 & 1 & 0\end{bmatrix},$$

$$D_C^+ = \max\left(0, -\begin{bmatrix}0 & 0 & 1 & 0\end{bmatrix}\right) - \min\left(0, \begin{bmatrix}0 & -1 & 1 & 0\end{bmatrix}\right) =$$

$$= \begin{bmatrix}0 & 0 & 0 & 0\end{bmatrix} - \begin{bmatrix}0 & -1 & 0 & 0\end{bmatrix} = \begin{bmatrix}0 & 1 & 0 & 0\end{bmatrix}.$$

e

$$\mu_{C_0} = b - L\mu_{P_0} = 0 - 0 = 0.$$

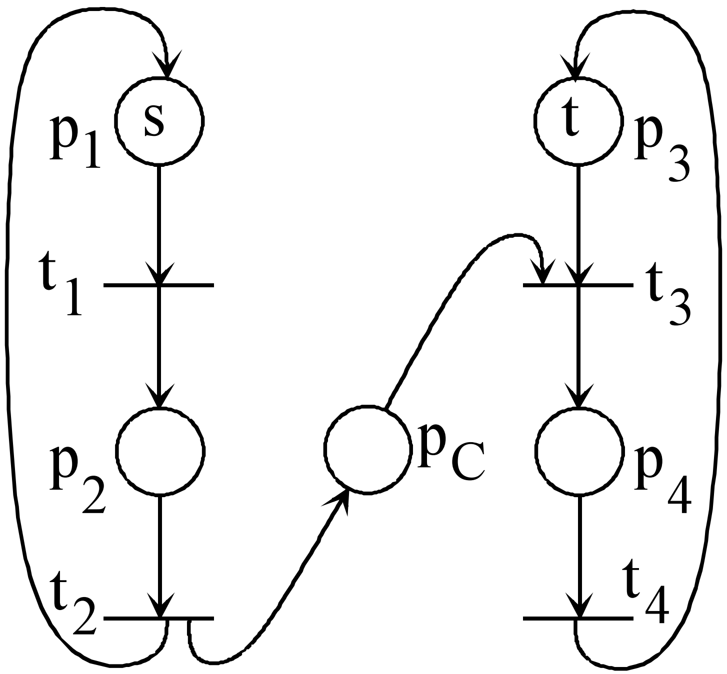
OK.

Methods of Synthesis

Example of controller synthesis

Producer / Consumer

3) Resulting in



$$D = \begin{bmatrix} -1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & -1 \\ 0 & 1 & -1 & 0 \end{bmatrix}$$

$$\mu_0 = \begin{bmatrix} s \\ 0 \\ t \\ 0 \\ 0 \end{bmatrix}$$

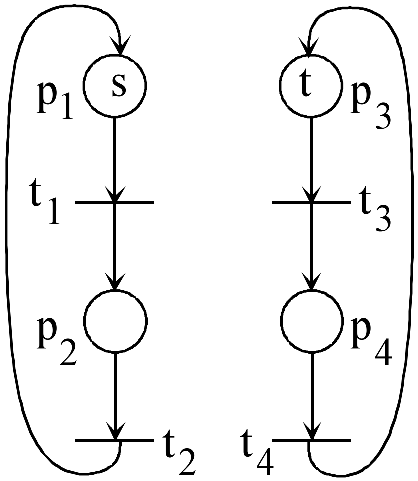
OK.
UAU!!!.

Methods of Synthesis

$$\forall s \in N_0, \forall t \in N_0, \forall n \in N_0$$

Example of controller synthesis

Bounded Producer / Consumer



TWO linear constraints:

$$v_2 - v_3 \leq n$$

$$v_3 - v_2 \leq n$$

That can be written as:

$$Cv_P \leq b \qquad \begin{bmatrix} 0 & -1 & 1 & 0 \\ 0 & 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} \leq \begin{bmatrix} n \\ n \end{bmatrix}.$$

$$L = 0, F = 0$$

Incidence matrix

$$D_P = \begin{bmatrix} -1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & -1 \end{bmatrix}$$

Initial marking

$$\mu_{P_0} = \begin{bmatrix} s \\ 0 \\ t \\ 0 \end{bmatrix}.$$

Methods of Synthesis

Example of controller synthesis

Bounded Producer / Consumer

1) Test $$b - L\mu_{P_0} = \begin{bmatrix} n \\ n \end{bmatrix} \geq 0.$$ **OK.**

2) Compute

$$D_C^- = \max\left(0, \begin{bmatrix} 0 & -1 & 1 & 0 \\ 0 & 1 & -1 & 0 \end{bmatrix}, 0\right) = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix},$$

$$D_C^+ = \max\left(0, 0 - \max\left(0, \begin{bmatrix} 0 & -1 & 1 & 0 \\ 0 & 1 & -1 & 0 \end{bmatrix}\right)\right) - \min\left(0, \begin{bmatrix} 0 & -1 & 1 & 0 \\ 0 & 1 & -1 & 0 \end{bmatrix}\right) =$$

$$\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} - \begin{bmatrix} 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}.$$

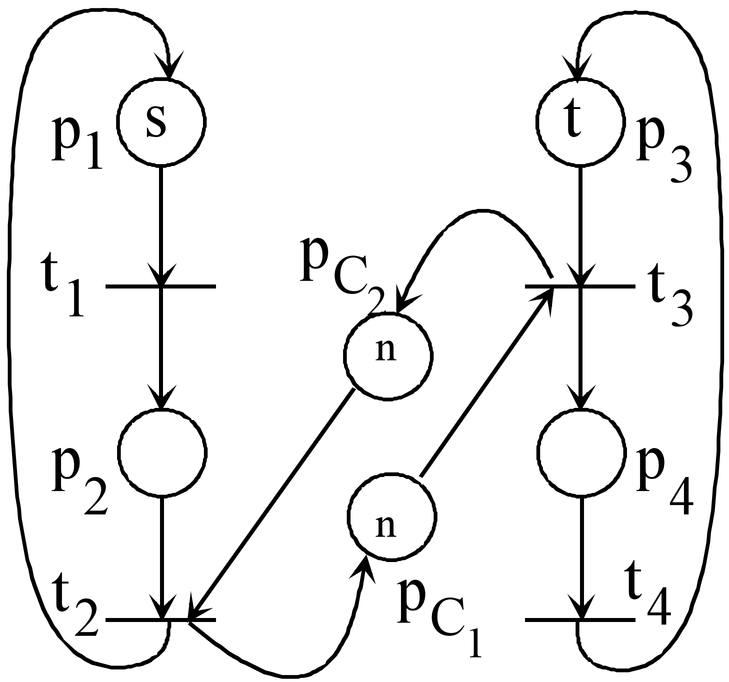
$$\mu_{C_0} = b - L\mu_{P_0} = \begin{bmatrix} n \\ n \end{bmatrix}.$$ **OK.**

Methods of Synthesis

Example of controller synthesis

Bounded Producer / Consumer

3) Resulting in



$$D = \begin{bmatrix} -1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & -1 \\ 0 & 1 & -1 & 0 \\ 0 & -1 & 1 & 0 \end{bmatrix}$$

$$\mu_0 = \begin{bmatrix} s \\ 0 \\ t \\ 0 \\ n \\ n \end{bmatrix}$$

OK.
UAU!!!.

Methods of Synthesis

Definition of Uncontrolable Transition:

A transition is uncontrolable if its firing can be inhibited by an external action (e.g. A supervisory controller).

Definition of Unobservable Transition:

A transition is unobservable if its firing can not be detected or measured (therefore the study of any supervisory controller can not depend from that firing).

Proposition:

A controller can not have arcs that connect to unobservable Transitions, then all unobservable transitions are implicitly uncontrolables.

Methods of Synthesis

Definition: A marking is admissible if

i) $L\mu_P \leq b,$

e

ii)

$$\forall \mu' \in R(C, \mu_{P_0}) \quad verifies \quad L\mu' \leq b.$$

Definition: A Linear Constraint is admissible if

i) $L\mu_{P_0} \leq b,$

and

ii) $\forall \mu' \in R(C, \mu_{P_0}) \quad such\,that \quad L\mu' \leq b,$

is an admissible marking.

Methods of Synthesis

Proposition: Admissibility of a constraint

A linear constraint is admissible iff

- The initial markings satisfy the constraint.
- There exist a controller with maximal permissivity that forces the constraint and does not inhibit any uncontrolable transition.

Corolary: given a system with uncontrolable transitions,

$\boxed{l^T D_{uc} \leq 0}$ implies admissibility.

Corolary: given a system with unobservable transitions,

$\boxed{l^T D_{uo} = 0}$ implies admissibility.

Methods of Synthesis

Function MRO_ADM da SPNBOX

Lemma: Structure of Constraint transformation

Let $R_1 \in Z^{n_C \times n}$ *such that* $R_1 \mu_P \geq 0,$

$R_2 \in Z^{n_C \times n_C}$ be a matrix with positive elements in the diagonal,

If there exists

$$L' = R_1 + R_2 L$$

$$b' = R_2(b+1) - 1,$$

such that $L' \mu_P \leq b'$

then it is also verified that $L \mu_P \leq b.$

The End.