CAN Worst Case Study: A New Approach

T. M. Querido[1,3], P. L. S. Aquino[1] , A.M. C. Neves[1] , V. B. Santos[1] and W. Lawrenz[2]

Abstract: Substantial work has been done on the problem of optimizing messages transmission on the Controller Area Network (CAN). Due to its hard combinatorial nature, CAN is a challenge for those who deal with the analysis of optimal ordering. In this paper, we present a new scheme on the worst-case response time of messages, considering a theoretical approach which allows the use of known optimization procedures.

1 - Introduction:

The fast increase on the use of distributed control systems in several industrial processes, together with the challenging search of an optimal scheduling mechanism justifies the great interest in this subject. We study real-time control systems where computer control nodes are connected via a communication network to coordinate demand of messages.

Control variables are typically periodic. The different periods are designed by control specifications of the distributed system. To reduce message transmission delay and thus obtain high communication channel utilization, the controller network employs message priority scheme.

In this paper we focus on CAN (Controller Area Network) - an important application of hard real-time distributed system, where processor nodes are connected by one or more CAN communication channels and each node uses pre-emptive scheduling to select running tasks. Due to its combinatorial nature, CAN is a challenge for those who deal with the analysis of optimal ordering.

The SAE (Society of Automotive Engineering) benchmark for class C automotive systems concerning safety critical control applications [1] is considered in this paper where the number of processing nodes, tasks set, size of messages (given in bits or milliseconds) [4], periods and their priorities (assumed as deadlines of messages) are given. Table 1.1 shows some SAE specifications. Due to the interference of different message transmission periods, the time intervals between successive instances of the same periodic message may suffer some fluctuations. This is the so called *jitter*.

Jitter may also occur as consequence of noise or EMI, despite the robustness of the considered network.

The jitter minimization has been studied as a combinatorial problem leading to an enormous number of different combinations which suggests the use of algorithms for the optimization of the parameters. In [13] a mathematical formulation of the problem was presented and the algorithm simulated

---

[1] Centro Federal de Educação Tecnológica CSF - Brazil

[2] Fachhochschule Braunschweig/Wolfenbuettel – Germany

[3] Supported by CNPQ (Conselho Nacional de Desenvolvimento Científico e Tecnológico)

annealing used to minimize the jitter. In [2] a modification of the genetic algorithm was used together with a simulation of the process achieving a measure of fitness for the system. The control loops performance, considering jitter in the variables, was studied by [9] and [16]. Other issue commonly studied is considering the worst-case analysis, i.e., the maximum amount of time a set of queued messages can take to arrive at their destination processors, as a parameter of fitness for the variables. In [17] the worst-case response time of a given message was given. In this work, we present a new scheme on the worst-case response of given messages in an interval of time. This approach allows to the identification of the maximum delay of a message, within its deadline, and to a fitness measure for the considered system.

Messages with shortest deadlines are assigned to highest priorities. Those messages compete for the exclusive use of a transmission. The use of algorithms is needed for determining, each time the system is available, which message should be sent next.

This paper is organized as follows. In section 2 we present a quadratic assignment problem model for the problem; section 3 outlines a worst case analysis, based on the quadratic assignment formulation. Finally, in section 4 we present some conclusions.

Signal Nunber	Signal Description	Size / bits	Period / ms	Periodic / Sporadic	Daed Line / ms	O(p)
1	Traction Batt. Voltage	8	100	P	100	2
2	Traction Batt. Current	8	100	P	100	2
3	Traction Batt. Temp. av.	8	1000	P	1000	1
4	Auxil. Batt. Voltage	8	100	P	100	2
5	Tract. batt. temp. max	8	1000	P	1000	1
6	Auxil. Batt.current	8	100	P	100	2
7	Accelerator position	8	5	P	5	5
8	Brake press., mas. Cil	8	5	P	5	5
9	Brake press., lire	8	5	P	5	5
10	Transaxle lubr. Press	8	100	P	100	2
11	Transac.cl. line press	8	5	P	5	5
12	Vehicle speed	8	100	P	100	2
13	Tract. Batt. grou. fault	1	1000	P	1000	1
14	Hi&lo cont. open/close	4	50	S	5	5
15	Key switch run	1	50	S	20	3
16	Key switch start	1	50	S	20	3
17	Accelerator switch	2	50	S	20	3
18	Brake switch	1	50	S	20	3
19	Emergency brake	1	50	S	20	3
20	Shift lever (PRNDL)	3	50	S	20	3
21	Motor/trans over temper	2	1000	P	1000	1
22	Speed control	3	50	S	20	3
23	12V power ack veh. Cont	1	50	S	20	3
24	12V power ack inverter	1	50	S	20	3
25	12V power ack I/M cont	1	50	S	20	3
26	Brake mode(parallel/split)	1	50	S	20	3
27	SOC reset	1	50	S	20	3
28	Interlock	1	50	S	20	3
29	High contrac. Control	8	10	P	10	4
30	Low contrac. Control	8	10	P	10	4
31	Reverse ans 2nd gear cl	2	50	S	20	3
32	Clutch press. Control	8	5	P	5	5
33	DC/DC converter	1	1000	P	1000	1
34	DC/DC conv. Curr. Cont	8	50	S	20	3
35	12V power relay	1	50	S	20	3
36	Traction batt. gr. fault test	2	1000	P	1000	1
37	Brake solenoid	1	50	S	20	3
38	Backup alarm	1	50	S	20	3
39	Warning lights	7	50	S	20	3
40	Key switch	1	50	S	20	3
41	Main contractor close	1	50	S	20	3
42	Torque command	8	5	P	5	5
43	Torque measured	8	5	P	5	5
44	FWD/REV	1	50	S	20	3
45	FWD/REV Ack	1	50	S	20	3
46	Idle	1	50	S	20	3
47	Inhibit	1	50	S	20	3
48	Shift in progress	1	50	S	20	3
49	Processed motor speed	8	5	P	5	5
50	Inverter temp. status	2	50	S	20	3
51	Shutdown	1	50	S	20	3
52	Status/malfuction(TBD)	8	50	S	20	3
53	Main contractor acknowled	1	50	S	20	3

Table 1.1- Some requirements of the messages in SAE to be scheduled

2 - Quadratic assignment

$$k_p \neq k_q \Rightarrow d_{pq} = dist(p,q) = (k_q - 1) - h(p,k_p)$$

$$k_p = k_q \Rightarrow d_{pq} = dist(p,q) = 0 \qquad (2.5)$$

formulation:

Given the set {1, 2, …, *N*}, the Quadratic Assignment Problem (QAP) can be stated as:

Minimize $\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{p=1}^{N}\sum_{q=1}^{N} f_{ij}d_{pq}x_{ip}x_{jq}$ (2.1)

For the location theory [10], F= [f_{ij}] represents the flow matrix where f_{ij} is the quantity shipped from plant i to plant j and D = [d_{pq}] represents the distance matrix where d_{pq} is the distance from location p to location q . The cost of simultaneously locating plant i to location p and plant j to location q is $f_{ij}d_{pq}$.
Complete surveys on QAP can be found in [5] and [13]. Applications of the QAP can be found in Çela [5], Dell'Amico et al. [6], Pardalos and Wolkowicz [13] and include plant layout problems, computer backboard wiring problems, control panel problems, among others.
It is necessary for a QAP formulation to have all parameters, including time quantity, in a finite amount. In hard real-time systems each message can be expressed in terms of indivisible blocks and the total period taken in interval [0, *N*] must be partitioned into equal indivisible time slots. The value of N was chosen as a multiple of the maximum common divisor (MCD) over the given periods. Geoffrion and Graves [7] introduced a basic *time quantum* τ for quantization of time and production in a scheduling plan which induces a standard block size, allowing a proportional rate to the other parameters.
We have now the problem of minimizing the total "cost" of allocation of the slots of time into the blocks of messages. A formal model is presented after the establishment of an adequate objective function.

Formulation of a hard real-time system as a QAP

The mapping used by the model considers the slots of time (of messages) as the facilities, the positions in the interval [0,*N*] the possible locations, the complete sequence of messages defines the 0-1 flows and the minimum interval of time for beginning the transmission of one message after the completion of another determine the distances between them. The expression of the problem proceeds as follows.
For a given interval [0,*N*], a given set of M messages μ_p^k , *p* = 1, ..., M, with period T_p , size σ_p , deadline D_p and considering k_p the current instance of message μ_p^k , k_p = 1, ..., $\frac{N}{T_m}$, where $T_m = MCD_p\{T_p\}$, define

$$h(p,k_p) = (k_p - 1)T_m + \sigma_p \qquad (2.4)$$

Observe that $h(p,k_p)$ depends on the instance *k* and the size of the message. It describes the position where the system will be available after message μ_p^k was sent.
The (*NxN*) matrices F = [f_{ij}] and D = [d_{pq}] are defined as follows.

$$f_{ij} = \begin{cases} 1, & if\ i = j+1, \\ 0, & otherwise. \end{cases} \qquad (2.6)$$

Consequently, by means of (2.3) - (2.6), we set the formulation for a hard real-time system as a QAP, which minimizes the total jitter in the interval [0,N].

$$g(p,k_p) = k_p D_p - \sum_{o(i)<o(p)} \sigma_i$$

Min $\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{p=1}^{N}\sum_{q=1}^{N} f_{ij}d_{pq}x_{ip}x_{jq}$

Subject to

$$\sum_{j=1}^{N} x_{ij} = 1 , \quad i = 1, \ldots, N \qquad (2.7)$$

$$\sum_{j=1}^{N} x_{ij} = 1 , \quad j = 1, \ldots, N \qquad (2.8)$$

$x_{ij} \in \{0, 1\}$, $i = 1, \ldots, N, j = 1, \ldots, N$
(2.9)

Constraints (2.7) - (2.9) guarantee that one slot of time will be allocated to one message within its period T_p and vice-versa.

The mapping assumed in this paper is based on two data matrices which give flexibility on the parameters choice, allowing the inclusion of new items in the system. By the other side, those matrices lead to the study of lower bounds ([5], [8] and [13], among others).

Example 2.1 – As an example, we take 5 messages from SAE Benchmark (signals # 1, 7, 18, 19, 29) and we consider 4 instances for the system. The Simulated Annealing algorithm which has been successfully used for the QAP [15] was used here to minimize the jitter (objective function). The correspondent simulation is presented in fig. 2.1 and the obtained jitter was approximately 9.9 ms. Of course, this result does not correspond to a real-world situation, once the network is subject to support the 53 messages in different instances. For this reason, heuristics or enumerative optimization procedures are required to the search of a sub-optimal or optimal solution.

This approach allows the discussion of a fitness measure for the problem of allocating messages and suggests the worst-case study presented next.

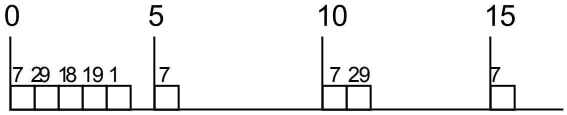

Fig.2.1 – Simulation of a system of 5 messages in 4 instances.

3 - A worst-case analysis

We now deal with the worst allocation of messages in the interval [0,N], i.e., messages are sent by its deadline. We assume a similar analysis to the hard real-time formulation as presented previously, with the necessary modifications to attend the new context. Messages are ordered according to their priorities: highest priorities are associated to messages with shortest deadlines. See table 1.1, where o(p) is referred to the priority order given to message p.

Consider the following function, as the position where μ_p^k can be sent without violating its deadline:

Follows the definition of matrix D = [d_{pq}]:

(2.10)

$$k_p \neq k_q \Rightarrow d_{pq} = g(q, k_q) - k_p + \sum_{o(i) > o(p)} \sigma_i$$

$$k_p = k_q \Rightarrow d_{pq} = 0$$

and matrix F = [f_{ij}]:

$$f_{ij} = \begin{cases} 1, & if\, i = j + 1, \\ 0, & otherwise. \end{cases} \qquad (2.11)$$

For the worst-case analysis the Simulated Annealing algorithm was also used to achieve the results for the set of messages in the same interval considered in example 2.1. Fig. 3.1 ilustrates the messages sent in their worst case. Observe that message #1 is not visible in the interval [0,20].

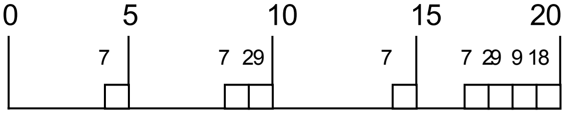

Fig.3.1 – Simulation of the worst-case.

- Conclusions

In this work we presented a novel application for the QAP in the context of hard real-time distributed systems. The problem formulation as a QAP can garantee the optimal identifier ordering and a suitable worst-case analysis, allowing to flexibility for new prototypes. By means of this approximation, we are opening to the control systems theory a new vision, yielding a mathematical formulation in a combinatorial optimization basis. The wide range of techniques to solve optimally or sub-optimally the QAP allows the systems analyst to chose the most suitable one.

References

[1] *Class C application requirement considerations,* SAE Technical Report J2056/1 (June 1993)

[2] J. Barreiros, E. Costa, J. Fonseca, F. Coutinho, J*itter reduction in a real-time message transmission system using genetic algorithms,* Proceedings of the CEC 2000 - Conference of Evolutionary Computation, (2000).

[3] S. Borst, K. G. Ramakrishnan, *Optimization of template-driven scheduling mechanism: regularity measure & computational techniques,* Journal of Scheduling, 2, pp 19-33 (1999).

[4] A. Burns, K. Tindell, A. Wellings, F*ixed priority scheduling with deadlines prior to completion,* Proceedings Sixth Euromicro Workshop on Real-time Systems, IEEE Computer Society Press (1994).

[5] E. Çela, *The quadratic assignment problem: theory and algorithm,* in D.Z. Du and P.Pardalos (Editors), Kluwer Academic Publishers (1998).

[6] M. Dell'Amico, F. Maffioli and S. Martello, *Annotated bibliographies in combinatorial optimization,* John Wiley & Sons, Chichester (1997).

[7] A.M. Geoffrion and G. W. Graves, *Scheduling parallel production lines with changeover costs: practical application of a quadratic assignment / LP approach,* Operations Research , vol. 24, no. 4, (1976).

[8] P.M. Hahn, and T. L. Grant, *Lower Bounds for the Quadratic Assignment Problem Based Upon a Dual Formulation,* Operations Research, vol.46, no.6, Nov.-Dec., pp912-922, (1998).

[9] G. Juanole, *Modélisation et évaluation du protocole MAC du Réseau CAN,* École d'eté ETR - Applications, Réseaux et Systèmes, ENSMA (1999).

[10] T. C. Koopmans and M. Beckmann, *Assignment problems and the location of economic activities*, Econometrica, vol. 25, n.1, 53-76 (1957).

[11] H. Kopetz, G. Grunsteidl, *TTP- A protocol for Fault tolerant real-time systems,* IEEE Computer, 27(1), (1994).

[12] A. W. Marshall, I. Olkin, *Inequalities: theory of majorization and its applications,* Academic Press, New York (1979).

[13] P. Pardalos and H Wolkowicz, *The Quadratic Assignment Problem: a survey of recent developments* in P. Pardalos and H Wolkowicz (Editors), Quadratic Assignment and Related Problems, DIMACS Series in Discrete Math. Theoret. Comput. Sci., vol.16, AMS, Providence, (1994).

[14] T.M. Querido, P.L. Aquino, A.G.Rua and C.L. Augusto, *Hard real-time*

distributed systems – A new perspective using quadratic assignment problem approach, INFORMS Meeting, 2001, USA.
[15] T.M.Querido, N.M.M.Abreu and P.O.Boaventura-Netto, *Redinv-SA: a simulated annealing for the quadratic assignment problem*, RAIRO Operations Research 33 (1999) 249-273.
[16] Stothert et al, *Effect of timing jitter on distributed computer control system performance* Proc. 15 IFAC Workshop in Distributed Computer Control Systems (1998).
[17] Tindell, K. and A Burns, *Garanteed Message Latencies for Distribute Safety-Critical Hard Real-time Networks, YCS 229, Department of Computer Science, Univ. of York, (1994).*

QUERIDO, Tania M.
CEFET-RJ
229, Maracanã Av. Rio de Janeiro
20271-110 RJ Brazil
tania@cefet-rj.br
www.cefet-rj.br

AQUINO, Paulo L. S.
CEFET-RJ
229, Maracanã Av. Rio de Janeiro
20271-110 RJ Brazil
aquino@cefet-rj.br
www.cefet-rj.br

NEVES, Antonio M. C.
CEFET-RJ
229, Maracanã Av. Rio de Janeiro
20271-110 RJ Brazil
mauricio@cefet-rj.br
www.cefet-rj.br

SANTOS, Víctor B.
CEFET-RJ
229, Maracanã Av. Rio de Janeiro
20271-110 RJ Brazil
victorsantos@cefet-rj
www.cefet-rj.br

LAWRENZ, W.
Fachhochschule
Braunschweig/Wolfenbuettel
Salzdahlumerstrabe 46-48
D38302 Wolfenbuettel, Germany
lawrenz@fh-wolfenbuettel.de