DISCO – DIStributed Embeddable Systems for COntrol Applications: Project Overview

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Abstract

Fieldbus based distributed systems used in real-time applications tend to be inflexible and are often developed without taking into account the possibility to adapt on-line application requirements such as control parameters. In this paper it is presented an overview of a project called DISCO that aims at achieving better, simpler and more flexible solutions for distributed embedded systems used in control applications (robotics, automotive, machine tools, …). It ranges from analyzing solutions to get flexible control requirements (e.g. period) and to cope with the influence of the network in the timeliness of control variables, it includes the improvement of medium access control protocols and it deals with the use of hardware based architectures to enhance systems responsiveness. Some of the results already achieved concerning the referred lines of work will be discussed in the paper as well as some on-going work and future developments.

Resumo

Os sistemas distribuídos baseados em barramentos de campo, utilizados em aplicações de tempo real, são quase sempre inflexíveis e raramente tomam em consideração a possibilidade de adaptar dinamicamente requisitos prévios da aplicação em causa, tais como parâmetros de controlo. Neste artigo apresentam-se de forma resumida as principais linhas de trabalho realizadas no âmbito de um projecto designado por DISCO. Os objectivos do mesmo consistem em tentar obter soluções mais flexíveis, mais simples e de melhor desempenho para sistemas distribuídos integrados em aplicações de controlo (robótica, automóveis, máquinas ferramentas, …). O projecto cobre um espectro de assuntos que se inicia na determinação de requisitos de controlo flexíveis (por exemplo período) e estudo da influência da rede na temporização das variáveis de controlo. Inclui a busca de melhorias no controlo do acesso ao meio de comunicação e o estudo e desenvolvimento de soluções em hardware para aumentar a velocidade de resposta dos sistemas. Neste artigo apresentam-se resumidamente alguns resultados já obtidos no decurso do projecto e indicam-se quais são os trabalhos em curso e os previstos para o futuro.

1. Introduction

Fieldbus based distributed systems find wide dissemination in embedded control applications, particularly in real-time systems for the automotive and robotics fields. To fulfil real-time constraints, current solutions tend to be inflexible or over sized, not reflecting much of the adaptability that could be extracted from a QoS (Quality-of-Service) based analysis of the control requirements.

The DISCO project aims at investigating techniques to improve flexibility and adaptability in distributed embedded control systems in order to reduce operation and maintenance costs while maximizing the utilization of system resources. Three main topics are being addressed:

- Flexible control requirements
- Infrastructural solutions
- Global systems management

In the first topic, it is intended to explore a QoS-based analysis of control requirements which will allow the establishment of operational ranges for the parameters typically used in system identification and control algorithms (e.g. sampling period, sampling and actuation jitter). Also, the partition of control operations in sub-tasks and their overall synchronization will be studied in order to minimize the effects of network-induced jitter.

In what concerns the so called infrastructural solutions, there is some further development of scheduling, dispatching and synchronization techniques already under investigation by the project team (planning scheduler [20], FTT-CAN [21], FPGA-based schedulers [22]). These solutions will improve flexibility and responsiveness and it is expected that they will permit the distributed system to accept on-line parameter changes within the ranges imposed by control requirements. Two parallel lines are followed.

In the first line, called the soft-line, scheduling and dispatching techniques, new or specifically adapted communication protocols, synchronization, handling of transient situations, are under investigation. These solutions are tested in systems based in off-the-shelf hardware.

The second one, the hard-line, consists in the development of hardware based solutions such as FPGA co-processors. These solutions seem promising to enable the use of dynamic scheduling algorithms which, when implemented in software, impose an overhead not compatible with the usual embedded processors.

In the last topic of the project, the global systems management, novel solutions to facilitate the development and operation of embedded distributed systems as a whole, integrating tasks and communication management are being studied. A network-centric perspective according to which all the flows of information in the system are controlled from the network is one of the lines of research. This perspective will be used to support the joint scheduling of tasks and messages in the global system. Synchronization services and global admission control will also be studied in this topic.

In the project, both simulation and experimental tests are used for results assessment. A CAN based distributed system developed locally [23] is used in many experiments and a portable demonstrator similar to a machine tool [24] in a final stage of construction will be quite helpful to evaluate real-time performance of many of the developed solutions.

The DISCO project involves the Portuguese institutions IEETA (Instituto de Engenharia Electrónica e Telemática de Aveiro – Universidade de Aveiro), IDMEC (Instituto de

Mecânica – Pólo do IST – Instituto Superior Técnico), IPCB (Instituto Politécnico de Castelo Branco) and ISEC (Instituto Superior de Engenharia de Coimbra). The project is funded by FCT – Fundação para a Ciência e Tecnologia and uses as consultants experts from the Lund Institute of Technology, Sweden, from the Institut National Polytechnique de Lorraine and Université Paul Sabatier, France and from Universidade de Pavia, Italy. It started in September 2000 and is expected to be finished in 2002.

After an overview of the state of the art in the field, the paper presents a brief discussion of the first results and of the work in progress under this project.

2. State of the art

Most industrial or embedded distributed control systems, rely on a fieldbus [1] to interconnect a set of nodes. When periodic variables are to be transmitted, it is possible to impose an average transmission period but, due to the interaction of other periodic, sporadic or aperiodic traffic, it is rather difficult to obtain constant time intervals between successive instances of the same periodic variable, leading to network induced jitter. This has a negative impact in control loops [2]. Recently, Stothert and MacLeod [3] revisited the subject of the degradation of controller performance due to jitter in the sampled and in the actuation variables and Juanole [4] studied the problem when a CAN – Controller Area Network [25] is concerned. The need for further research in communication jitter minimization was also pointed in [5]. Cervin [6] and Shin [7] address the same subject in the general real-time systems field, where changes in the period of control tasks were considered.

In order to support evolving changes in control requirements as well as to facilitate set-up and maintenance, operational flexibility is fundamental [8], even in embedded systems [9]. However, when on-line changes are required, real-time programming techniques rely mostly on best-effort paradigms [10] and thus timeliness is not fully guaranteed. The combination of the planning scheduler [20] with the elastic task model [11] and with dynamic techniques to change static schedules [12] seems promising to obtain operational flexibility in real-time systems, while maintaining timeliness guarantees. In any case, the research must be aware of the communication system as it is a fundamental element in any distributed system [9], [1].

Another important issue concerning mainly scalability and timeliness is the synchronization of tasks and messages. Fundamental results concerning deterministic algorithms [13] lead to considering the use of non-deterministic algorithms, e.g. [14], [15] for the synchronization between nodes.

In terms of the global management of distributed embedded systems, it is essential to consider the interdependencies between tasks and messages and, if possible, their joint scheduling, often referred as holistic [16]. Several studies like the works of Hong [17] and Navet [18] address this problem when a fieldbus is used as the system interconnection. However, those works consider previously defined sets of tasks and messages, while the possibility of introducing changes on-line is not adequately studied [10]. On the other hand, previous work combining flexibility with timeliness (the Spring kernel [19]) demanded a considerable run-time overhead. Techniques suitable to support on-line global management are required, to exploit new flexible integrated communication and control systems.

3. Influence of the network in controller performance

One of the research directions in this line is the evaluation of the impact of network induced sampling jitter and/or of “small” sampling period changes in system identification techniques

(e.g. least-squares, NN-based, neuro-fuzzy) and in discrete control algorithms (e.g. PID, pole-placement, NN-based, fuzzy, neuro-fuzzy).
Current work addressed the influence in system identification performance of a particular type of jitter induced by the specific MAC of CAN. The problem was studied using different priorities for the messages carrying sensor/actuator data. A jitter measure was obtained from a set of experiments [35] in which messages delays were recorded under a traffic load based on the PSA benchmark [36]. The experimental results show that, under very different working conditions, message delays in CAN can be represented by means of a Gamma distribution.
The effect of jitter can be viewed as a perturbation that introduces a variable delay in the reading of the samples and in the actuation signal sent to the plant. The existence of one or both of the situations depends on the distributed control system architecture (read-in and read-out jitter [3]). The first results [37] show that, when jitter is not taken into account, the model identification is poor when compared with the one that considers it as a fractional dead time. Simulations show improvements between 2.3 times and 7700 times for different control systems with different traffic loads (example in figure 1). Also, the use of a more complex model leads in most situations to some immunity to the influence of high transmission loads, independently of the priorities chosen for the relevant messages.

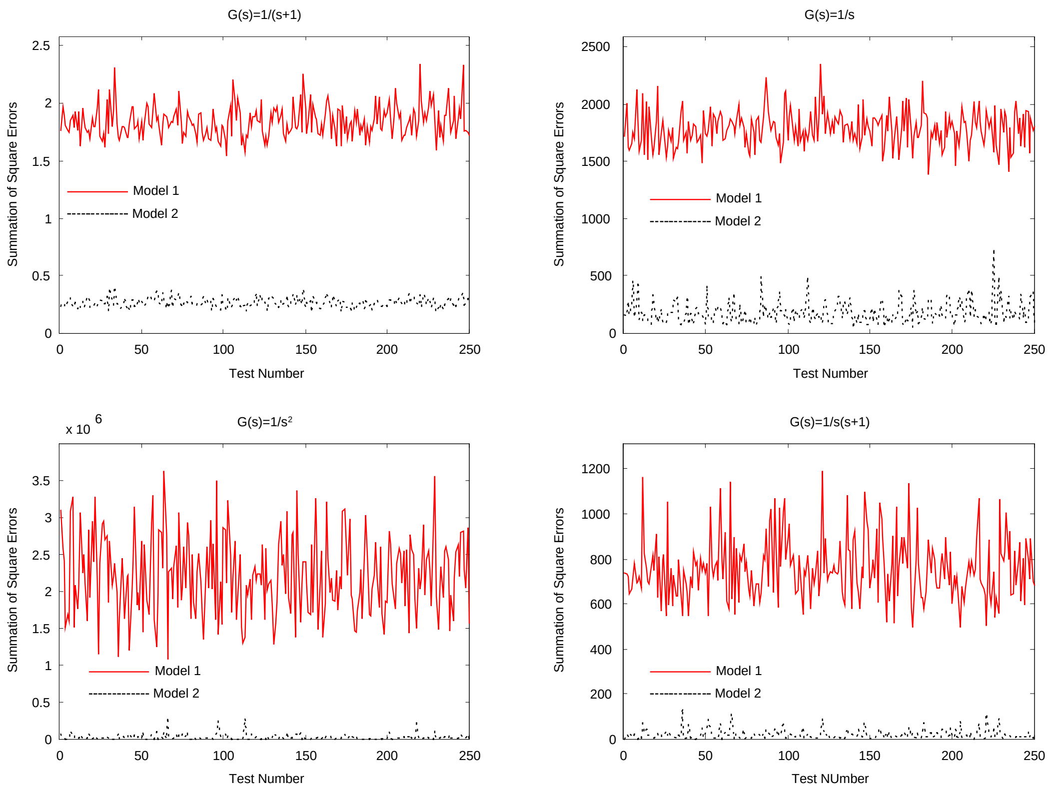

Figure 1 – Example of results for the network-induced jitter influence

4. Infrastructural solutions

4.1 Software-based solutions

The work in this line comes in the sequence of the planning scheduler [20] development. This technique is used to achieve flexibility without loosing real-time behavior. It can be used in fieldbuses with centralized dispatching to schedule a periodic message set that must be changed from time to time. The idea is to schedule the periodic traffic for consecutive fixed duration time intervals called plans. The plan is, in principle, considerably shorter than the one that would be needed to reflect the complete periodic traffic pattern (the minimum common multiple of the messages periods). This way it is possible to reduce the computational overhead of the scheduler to values compatible with on-line operation even with low-power microcontrollers. This technique can be applied to fieldbuses such as WorldFIP [26].

The planning scheduler and the reinforcement of the idea that time-triggered synchronization is better to guarantee real-time properties [9], led to the project of applying it to a typically event-triggered fieldbus such as CAN. The main interest comes from its use in embedded solutions for fields where real-time is mandatory as it is the case of automotive industry. It was then developed a new MAC protocol to operate over CAN which was called FTT-CAN [21]. In this protocol, a network arbiter or master, broadcasts a periodic message which contains a set of flags used to instruct the producer nodes in the system to broadcast their respective periodic messages. The arbiter node relies on a planning scheduler to define which messages must be transmitted.

The transmission of messages in FTT-CAN is carried out in short cycles called Elementary Cycles (ECs). Within each EC there are two consecutive windows, one dedicated to the transmission of periodic messages (synchronous window) and another to allow the transmission of normal event-triggered messages (asynchronous window). In the usual planning scheduler the changes in the message set only take effect after one or two plans (typical duration of a plan: 178ms for a 125Kbit/s fieldbus). This latency may be too long for certain real-time applications. To overcome this, further studies have been carried out in order to allow changes to the message set to take effect on the bus with a latency shorter than the period of the message being added or changed [27].

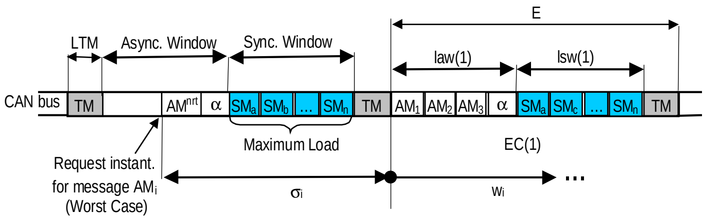

Figure 2 – Combining event-triggered and time-triggered traffic in FTT-CAN

However, in order to assure a continued timely service, schedulability analysis must be carried out before changes to the message set are done. Several studies were done to adapt the traditional schedulability analysis in systems where preemption is allowed to fieldbus based systems. One of the results [28] was an adaptation, for the non-preemptive situation, of the Liu & Layland [29] formulation. Another technique consists in building a timeline to verify if the first instance of the lower priority message in the set can still be transmitted without missing the deadline [30].

The advantages of using time-triggered synchronization in distributed systems was also recognized by automotive industries. This recognition led to the launching in January 2000 of a sub-task (ISO/WD 11898-4, TC 22/SC 3/WG 1, TF 6) under ISO – International Standards Organization to develop it on ISO-11898 as a session layer for CAN fieldbus. The standard which will appear soon is called TTCAN – Time triggered CAN. Members of the DISCO project team have been participating in the task force. TTCAN uses an off-line schedule to define the traffic that must be transmitted. Current work under the DISCO project consists in defining cost functions that will lead to improve the construction of TTCAN schedule. Also, software tools based on heuristics such as genetic algorithms are being used to build the schedule in the sequence of previous work to minimize jitter in CAN-based systems [31].

4.2 Hardware-based solutions

Implementing certain functions of a real-time multitasking operating system in dedicated hardware, is a known solution to improve the execution time and predictability of the operating system functions. The same approach can be explored in the area of industrial fieldbus networks to off-load the node processors from the computational effort imposed by dynamic or quasi-dynamic traffic scheduling strategies. This type of strategies will allow the operational parameters of the communication system to change on-line, e.g. when a new sensor is added or the update rate of an existing variable is increased.
As this task is practically impossible for the typical mid-range microcontrollers used in fieldbus nodes, it requires a specialized scheduling coprocessor. One of the approaches followed in the project is to develop custom processors based on FPGA (Field-Programmable Gate Array) technology which can then implement scheduling algorithms in hardware. An initial version of this coprocessor for the planning scheduler is already developed [32]. It is based on a XC4010 FPGA from Xilinx working with a 8051 microcontroller. The co-processor, called PSCoP and operating @ 12MHz, can schedule a set of 8 periodic variables for a plan with a length of 16 time units (EC – Elementary Cycles, see e.g. [20] for an explanation of the concept) with a worst case execution time of 63µs.

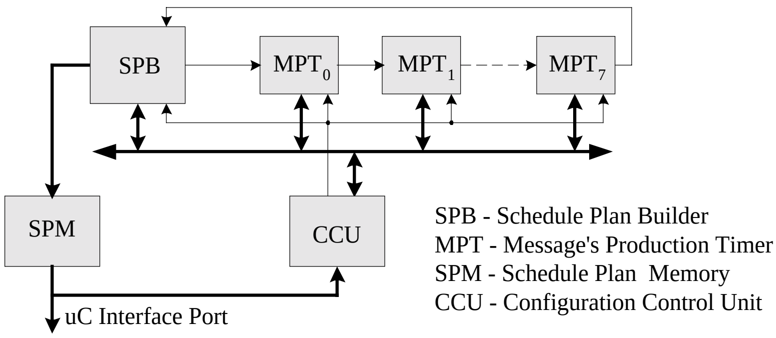

Figure 3 – Architecture of PSCoP scheduling co-processor

A study to improve this co-processor has already been done [33]**.** The next version will have increased features such as the possibility to choose the scheduling policy between rate monotonic, deadline monotonic or arbitrary priorities defined by the user and the inclusion of a schedulability analyzer based on the timeline method [30]. Also, the number of variables in the set will be increased and the interface with the node CPU will be improved.

5. Conclusions, Work-in-Progress and Future Work

In this paper, a brief view of the research work going on under the DISCO project was presented. As the project has just started on September 2000 most results are just partial and some important lines of work have not obtained yet relevant results.
At this moment there are significant results in what concerns the reduction of network-induced jitter in control systems supported on fieldbuses. Also the definition of a time-

triggered protocol for CAN, called FTT-CAN, is almost complete. This protocol can be used in hard-real time systems while offering adequate flexibility and responsiveness for automatic on-line change of system parameters. A first prototype of a hardware co-processor for scheduling operations is also finished. The measured performance shows that it is possible to use this type of solution to obtain quasi-dynamic scheduling. New versions of the co-processor are under development.

Future work includes evaluating the performance of different types of control algorithms under various jitter and period conditions. The figures of merit will be the quadratic-error, the settling time and the control effort whenever possible. Operational ranges with different QoS Quality of Service (from the control point of view) are expected to be obtained.

Using the infrastructural solutions under investigation it is expected to develop global management mechanisms capable, in particular, to perform a global admission control of new (dynamic) system requirements. One of those mechanisms can rely on a network-centric perspective [34] according to which all the flows of information in the system and the respective processing will be controlled from the network. This solution will facilitate a holistic and dynamic schedulability analysis taking into account the tasks running in the nodes and the messages transmitted over the network.

It is then expected to achieve more flexible and simpler distributed systems for embedded applications even if low-processing power off-the-shelf components and common fieldbus networks are to be used.

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