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研究課題名（和文）トーラスにおける耐クラスタ故障経路選択手法の探究と確立

研究課題名（英文）Cluster-fault-tolerant routing methods in tori

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研究成果の概要（和文）：トーラス位相に基づく相互結合網と関連課題を研究した。具体的には，超並列計算機に対する相互結合網の代表的な位相であるトーラスに焦点を当て，故障ノードのまとまりを故障クラスタとして処理することで，従来手法が想定する故障ノード数の2～数倍の故障ノードが存在しても，非故障ノード間に非故障経路を確立するアルゴリズムを提案し，その性能検証を行った。また、相互結合網の一つの課題である電力の消費も取り組んだ。

研究成果の学術的意義や社会的意義
Modern supercomputers include numerous compute nodes, called processors. In order to maximise the system performance, it is critical to efficiently connect all these nodes as it conditions efficient data transfers and usage in general of the processors.

研究成果の概要（英文）：Throughout this research project, we have conducted investigations regarding the interconnection network of massively parallel systems, such as supercomputers. We have especially focused on torus-based interconnects, and considered related theoretical problems such as routing algorithms and related graph theory problems. In addition, we have considered related practical problems, for instance thinking about how to reduce power consumption of interconnection networks since power consumption of modern supercomputers is an on-going issue. Concretely, we have investigated low-power devices and the corresponding technologies, and IoT devices in general to this end.

研究分野： computer systems

キーワード： interconnect　supercomputer　dependability　routing　graph　fault-tolerance

１．研究開始当初の背景

Whereas first-generation supercomputers consisted of few nodes only, modern parallel systems include hundreds of thousands of compute nodes, and even several millions for the newest machines like the Supercomputer Fugaku (RIKEN) and Frontier (DOE/SC/ORNL) machines. It is thus essential in order to maximise the system performance to be able to efficiently utilize this huge amount of compute nodes.

Interconnection of all these compute nodes is the role of the interconnection network, also simply called interconnect. The interconnect can thus be formalised as a non-directed graph of graph theory: it consists in nodes (vertices) and edges, with one node standing for one compute node of the supercomputer. The structure, or topology, of the corresponding graph is critical for the interconnect and supercomputer in general to achieve high performances.

Besides, it is important to note that the torus network topology has proven popular as interconnection network of modern supercomputers – this is for instance the case of the IBM Blue Gene/L, the IBM Blue Gene/P, the Cray Titan and the Fujitsu K supercomputers.

２．研究の目的

We have followed two main objectives in this research: first, the proposal and evaluation of new or improved data transfer methods for torus-based interconnection networks. For example, we aimed at solving the problem of routing data from one compute node to another inside a torus-based interconnect that may include clusters of faulty nodes.

Second, we have considered related issues of interconnection networks to further improve their performances. For example, we have investigated how to reduce the power consumption of interconnection networks.

３．研究の方法

Regarding our first objective, we have first proposed a cluster-fault tolerant routing algorithm in a torus network. This is a difficult problem, so we had to restrict the fault-tolerance to clusters of diameter at most one, that is clusters of at most two nodes.

Then, we have proposed a routing algorithm in a torus that this time selects several paths that are mutually node-disjoint. Moreover, the sources and destination pairs are set in advance. This is called the pairwise disjoint paths routing problem.

We have also worked on the decycling problem (a.k.a. the minimum feedback vertex set problem) in a torus so as to further improve data transfer efficiency by excluding cycles from the network.

Next, we have described a set-to-set disjoint paths routing algorithm in a bijective connection graph. This work was an attempt to further generalise the routing problem that we have addressed in the past, first and foremost for the torus network topology.

Back in the specific case of the torus topology, we have also considered the difficult crossing number problem, which is important for example for circuit design (e.g. for VLSI) and graph visualisation.

We have also considered minimal paths in a bicubes; it is well-known that hypercubes, on which are based bicubes, and tori are strongly related. And we have similarly worked with Möbius Cubes for which we have proposed a solution to the set-to-set disjoint paths routing problem

Regarding our second objective, we have considered power consumption reduction possibilities by relying on microcontrollers. Precisely, we have to this end investigated hardware and software development issues to enable the usage of microcontrollers in interconnection networks: debugging issues, memory optimisation issues, networking and data transfer issues, and programming issues summarise the methodologies we have followed.

４．研究成果

First, regarding the cluster-fault tolerant routing algorithm in a torus network, in an n-dimensional k-ary torus, this algorithm is able to select a fault-free path of length at most $n(2k+\lfloor k/2 \rfloor-2)$ in $O(n^2k^2|F|)$ time, where F is the set of faulty nodes (the faulty nodes are induced by the faulty clusters, obviously).

Second, the pairwise disjoint paths routing algorithm proposed in a torus is able to select mutually node-disjoint paths that are of lengths at most $\lfloor k/2 \rfloor n + (\lceil 3k/2 \rceil - 2)(c-1)$ with c $(c \leq n)$ the number of paths to find in $O(c^3 n + kcn)$ time.

Third, the minimum feedback vertex set problem has been addressed in a 3-dimensional k-ary torus network: a method to generate a decycling set of competitive size has been described and its time complexity $O(k^3)$ has been shown to be optimal.

Fourth, the set-to-set disjoint paths routing algorithm that has been proposed in a bijective connection graph is able to select p paths in an n-dimensional bijective connection graph $(p \leq n)$ whose lengths are at most $n + p - 1$. Besides, we have shown that the worst-cast time complexity of this algorithm is $O(n^3 p^4)$ and we have conducted a computer experiment to also derive its average time complexity: $O(n^2)$ and average maximum path length: $0.6333n - 0.266$.

Fifth, regarding the crossing number problem in a torus network, we have been able to show that the number of crossings in a 3-dimensional k-ary torus is at most $2k^4 - k^3 - 4k^2 - 2\lceil k/2 \rceil \lfloor k/2 \rfloor (k - (k \bmod 2))$. Furthermore, we have been able to generalise this result to an n-dimensional k-ary torus: $O(n^2 k^{2n-2})$ when $n \geq k$ and $O(nk^{2n-1})$ otherwise is an upper bound on the crossing number.

Sixth, we have shown that an optimal solution with respect to the path length when routing inside a bicube can be found in $O(n^2)$ time. And inside when finding disjoint paths between two sets of nodes inside an n-Möbius Cube, we have shown that n mutually node-disjoint paths can be found in $O(n^6)$ time, with each path being of length at most $2n - 2$.

Next, regarding the second objective of this research work, we have shown with practical experiments that it is possible to conduct on-chip debugging at a very low-cost. We have also shown that memory utilization on such minimalistic devices (microcontrollers) can be optimised to enable graphic display, which is obviously important for applications and debugging. Then, we have discussed methods on how to realise cost-efficient data transfers between such low-end devices and we were able to show that both power consumption and cost remains comparatively low (e.g. 2.5 W in the worst-case for five such minimal nodes, and about USD 33 to build one node).

Finally, we have successfully introduced a new programming paradigm, called SOF and originally thought for such minimal devices, which shows that it is possible and practical to program with an instruction-based approach, as with the assembly language, especially important for microcontrollers, but at the same time relying on functional programming strategies, like the absence or near absence of side effects. We showed with computer experiments that this programming paradigm's execution performance (time) is on a par with the C language and is faster than, although of course not as feature complete as, the functional languages Racket and Haskell.

These are the main achievements of this research project.

参考文献

The above research methods, discussions and results are detailed in the papers listed in the rest of this report.

５．主な発表論文等

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
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７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関			
米国	University of Nevada, Reno			