Simulation of Blood Flow in a Ventricular Assist Device

Introduction
Diseases of the heart are a leading cause of death in the industrialized nations. The most reliable therapy for end-stage heart failure – heart replacement via a transplant – can be applied only in a fraction of the cases because of dramatic shortage of suitable donor hearts.

Since 1960’s, attempts are being made to design a mechanical solution to heart failure; such a solution can take the form of a full replica of the heart – dual pumping chambers and complex valves – or, more commonly, of an assisting device, which pumps the blood from the existing failing ventricle into the aorta. The latter are referred to as Ventricular Assist Device, or VAD.

The Chair for Computational Analysis of Technical Systems (CATS) at the RWTH Aachen University, under the direction of Prof. Marek Behr, is specializing in CFD analysis and has been working on simulation of blood flow in VADs since 2000, with the latest analyses focusing on the miniature MicroMed DeBakey VAD (see Figure 1). The main component of the DeBakey VAD is a spinning impeller propelling the fluid towards its destination and building up the required pressure head.

Simulation
CATS uses compute-intensive simulations to explore the potential of each design modification of the VAD, running a variety of flow profiles, flow rates, and impeller speeds to find the best way to improve the pump’s biocompatibility.

Design challenges are staggering: the pumps need to be very small in order to be easily implantable, and they need to produce blood flow patterns that most closely resemble those in the body, in order to prevent hemolysis and thrombosis.

Hemolysis – the release of hemoglobin into the bloodstream – can result from damage to fragile red blood cells caused by prolonged elevated stresses imparted by the flow field. It is a potential danger to internal organs and can be life-threatening in extreme cases. In a VAD where the impeller spins at 10,000 rpm the shear stresses can be much higher than under physiological conditions.

Thrombosis – clotting of blood – can be caused by abrupt changes in the flow pattern and may lead to device malfunction or strokes.

These flow features can be predicted by simulations, but with a complex geometry such as DeBakey VAD, computational meshes in excess of 5 million computational cells are required for adequate accuracy. Thousands of discrete time intervals must be followed for simulating just a few revolutions of the impeller (see Figures 2 and 3).
In December 2006, a scaling workshop for applications running on the 8-rack Blue Gene/L system in Jülich was organized and sponsored jointly by the John von Neumann Institute for Computing (NIC), IBM and the Blue Gene Consortium [1].

Prior to the workshop, one could observe an acceptable scaling of XNS up to 1,024 processors while there was no significant speed-up above that (see Figure 4). To find the bottlenecks in the code, the communication between the processes during the simulation runs was analyzed, both with XNS internal time measurements and the SCALASCA package [2]. After improving the communication patterns of XNS, the simulation performance could be improved remarkably up to 4,096 processes (see Figure 4). A good scaling is expected also for 8,192 processes; this is to be analyzed in future test runs.

CATS will continue its analysis of the DeBakey VAD with the objective of further improving the pump design and reducing its size, so that it could be used also for pediatric applications. The possibility to make efficient use of up to one fourth of the processors available on the Blue Gene/L at Forschungszentrum Jülich, one of Europe’s most powerful computers is of great value here, because it allows generating the required data in a reasonable time.

Due to the many areas where XNS can be applied and its good scalability, we are confident that we could make efficient use of even bigger machines than the current Blue Gene/L.

References
[1] Frings, W., Hermanns, M.A., Mohr, B., Orth, B.
Report on the Jülich Blue Gene/L Scaling Workshop 2006
Scalable Parallel Trace-Based Performance Analysis
inSiDE Vol. 4, No. 2, 2006

Parallel Computing
The parallel implementation is based on message passing communication libraries, exploits graph-based mesh-partitioning techniques, and is portable across a wide range of computer architectures. The simulation for the DeBakey application is so complex that even on a large number of processors a full prediction of a quasi-stationary flow field in a DeBakey pump may take many hours.

With simulations being repeated to proceed towards substantial design improvements, it becomes crucial to be able to exploit very large numbers of processors simultaneously, for example, the 16,384-processor IBM Blue Gene/L system operated by the Forschungszentrum Jülich.

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