Efficient simulation of Water Distribution Systems using OpenMP

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Abstract

Hydraulic solvers for the simulation of flows and pressures in water distribution systems (WDS) are used extensively, and their computational performance is key when considering optimization problems. This paper presents an approach to speedup the hydrualic solver using OpenMP. The procedure is based on a parallel algorithm for the generation of the linear system of equations. Preliminary results show the validity of the approach.

Key words: OpenMP, Parallel Simulation, Water Distribution Systems

1 Introduction

Hydraulic solvers for the simulation of flows and pressures in water distribution systems (WDS) are used extensively to solve a large number of problems, such as network optimal design, maintenance, model calibration or risk analysis problems. In many cases the simulation needs to be repeated many times within an optimization framework. Thus, the computational performance of the hydraulic solver is extremely important.

There have been different approaches for the use of HPC in the simulation of WDS: [1] explores the parallelization in distributed memory platforms using MPI. [2] considers the use of vector (SIMD) instructions of current processors, and also Graphics Processing Units (GPU). The work in [3] also focuses on the use of GPU.
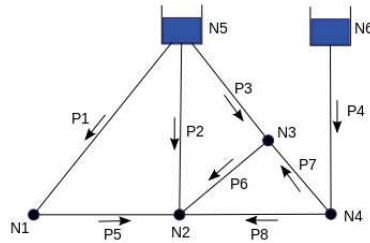
Figure 1: Sample water supply network

In this paper we explore the use of OpenMP for WDS simulation. In the next section we present the problem, and focus on the generation of the linear system of equations, which is the part that is considered for parallelization. The approach followed is described in section 3. Preliminary results and conclusions are provided next.

2   WDS Simulation

The problem of WDS simulation considered in this paper consists of computing the flows and heads in a network of pipes for water distribution, under the assumption of steady-state conditions. The network consists of m link elements (pipes, valves and pumps) connected to $n + n_s$ nodes (n junctions and n_s source nodes). Figure 1 shows a simple network with 8 links (pipes P1-P8) and 6 nodes (the 4 junctions N1-N4 and the 2 source nodes or tanks N5-N6).

One of the most effective methods for the simulations of WDS is the Global Gradient Algorithm (GGA) [4], which is a Newton-Raphson method requiring at each iteration the solution of a linear system with a sparse, symmetric positive definite $n \times n$ matrix. The GGA is the method of choice for Epanet [5], a public domain WDS modeling software package considered a reference software in this field. In this paper, Epanet is taken as the reference sequential implementation.

The generation of the linear system in each iteration is one of the most computationally intensive parts in the simulation of WDS [2], [6]. It entails the computation of two values, p_k and y_k, for each link, and the assembly of those values in the system matrix and vector. In the case of pipes, the two values are obtained as

$$p_k = \frac{1}{\beta r |q|^{\beta-1} + 2\rho|q|}, \ \ y_k = p_k q(r|q|^{\beta-1} + \rho|q|)$$

where q is the flow through the pipe, r and ρ are resistance coefficients for each particular pipe, and β is a constant exponent.

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Algorithm 1 presents a simplified version of the procedure to generate the linear system. A more complete description of this procedure can be found in [5].

Algorithm 1 Linear system generation (simplified version)

Input: For each of the m links: end nodes, coeffs. r, ρ, flow approximation q
  Matrix A, vector b, both set to zeros
Output: Matrix A, vector b
  for $k = 1, 2 \cdots m$ **do**
    $p_k \leftarrow \frac{1}{\beta r |q|^{\beta-1} + 2\rho|q|}$
    $y_k \leftarrow p_k q(r|q|^{\beta-1} + \rho|q|)$
    Let i, j be the indices of the end nodes of link k, with $i \geq j$
    $a_{i,j} \leftarrow a_{i,j} - p_k$
    $a_{i,i} \leftarrow a_{i,i} + p_k$
    $a_{j,j} \leftarrow a_{j,j} + p_k$
    $b_i \leftarrow b_i + y_k$
    $b_j \leftarrow b_j + y_k$
  end for

Since the matrix A is symmetric and sparse, Epanet stores only its triangular half, and uses *compressed sparse column* (CSC) format. The necessary data structures are created for fast access to matrix elements corresponding to any given link or node.

3 Parallelization approach

The parallel algorithm 2 is proposed for the generation of the linear system. As can be seen, the loop in the sequential algorithm has been split in two, the first one going over the links, and the second one going over the junctions. Each of the resulting loops has no dependencies between iterations, and thus can be parallelized in a straight-forward way.

It has to be taken into account that the parallel algorithm needs to use the appropriate data structures to obtain in a fast way the list of links connected to any network node.

4 Results

Table 1 presents preliminary timing results for the parallel algorithm presented in this paper. The results correspond to a real water distribution network with 29,345 links and 25,813 junction nodes. The row "newcoeffs" refers to the parallel algorithm for the generation of the linear system, while "total" corresponds to the whole simulation.

It can be seen that the time for the generation of the linear system reduces considerably, with a maximum speedup of 5.6 with 16 threads. Considering the whole simulation, the

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Algorithm 2 Linear system generation in parallel (simplified version)

Input: For each of the m links: end nodes, coeffs. r, ρ, flow approximation q

Matrix A, vector b, both set to zeros

Output: Matrix A, vector b

  # *parallel for directive*

  for $k = 1, 2 \cdots m$ **do**

    $p_k \leftarrow \frac{1}{\beta r |q|^{\beta - 1} + 2\rho |q|}$

    $y_k \leftarrow p_k q (r|q|^{\beta - 1} + \rho |q|)$

    Let i, j be the indices of the end nodes of link k, with $i \geq j$

    $a_{i,j} \leftarrow a_{i,j} - p_k$

  end for

  # *parallel for directive*

  for $i = 1, 2 \cdots n$ **do**

    for all k such that link k is connected to node i **do**

      $a_{i,i} \leftarrow a_{i,i} + p_k$

      $b_i \leftarrow b_i + y_k$

    end for

  end for

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threads	1	2	4	8	16	32
total	2.13	1.72	1.45	1.37	1.55	1.7
newcoeffs	1.06	0.66	0.39	0.24	0.19	0.24

Table 1: Times (in secs.) for the simulation of a real network

reduction in time is more moderate, the fastest time corresponding to 8 threads, with a speedup of 1.55.

5   Conclusions

An approach has been described to speedup the simulation of WDS using OpenMP.

The results, although preliminary, show that the simulation of WDS can benefit from the parallelization by means this approach. Taking into account that problems such as network design or network optimization make an intensive use of simulation, the increase of speed shown in this paper can have a great impact on the time needed to solve such problems.

More complete results will be presented in a future paper.

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