Concurrent dynamic programming for grid-based problems and its application for real-time path planning

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HIGHLIGHTS
- We present a highly concurrent grid-based robot motion planner.
- The planner is implemented to run on modern graphics hardware.
- The algorithm runs in $O(N)$ time for $N$ cells in the grid.
- Can exhaustively plan on a 50ha campus with 1 m × 1 m resolution in real-time.

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ABSTRACT
This paper presents a concurrent approach for solving dynamic programming optimization problems such as the generation of optimal cost-to-go functions for robot motion planning in dense environments. Such optimization techniques are core to many robotics problems, but traditional approaches are inherently impractical due to their computational complexity. This limitation usually results in a configuration space being subsampled, lower configuration space coverage, less frequent planner updates, or the use of sub-optimal graph-based roadmap methods. The proposed approach provides mathematically identical results to traditional grid-based motion planning solvers in at least an order of magnitude less time by leveraging the concurrent architecture found in modern graphics hardware. Although results given here are presented in a robot navigation context, they are also applicable to other dynamic programming problems.

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1. Introduction

A current robust and accurate method of robot motion planning involves representing an environment as a grid-based configuration space. For example, [1] use laser range sensor data to construct a two-dimensional occupancy grid before generating an exhaustive cost-to-go function for planning. An optimal path is then extracted from the cost-to-go function, similar to [2], and is approximated to a nonholonomic solution under the constraints of the Unmanned Ground Vehicle’s (UGV’s) dynamic model. While planning on grid-based configuration spaces is accurate, generating a cost-to-go function can be computationally expensive [3,4].

The remainder of this paper provides a review of existing robot motion planning techniques and highlights prior approaches that either suffer from or attempt to defer the computational complexity of existing grid-based motion planners. A brief background is given in Section 3 to provide the reader with context of the proposed approach. Each evolution of the algorithm and implementation is then presented in Section 4, with experimental results given to properly assess the performance of each flavor in Section 5. In particular, the differing flavors presented focus on reducing the number of repeated redundant calculations performed in the GPU together with minimizing CPU time managing these subregions, with the CPU management being performed post iteration. The flavors are summarized here as follows for the reader’s convenience:

Subregions - Grouping cells within an occupancy grid and choosing to evaluate cells within this group together on the graphics hardware to properly balance GPU execution time against CPU management time.

Caching subregion cell values - Caching a subregion’s cell values at the post iteration check of $t_i$ so they can be used again at the $t_{i+1}$ post iteration check without having to be re-read from the graphics hardware.
Delayed post iteration check  Performing the post iteration check
every 2nd and 3rd iteration.

Statistically scheduled post iteration check  Performing the post i-
teraction check on a schedule that targets the statistically
appropriate iterations to perform the check on.
A discussion is then raised in Section 5.6 on the generalized
performance of the concurrent algorithm relative to a traditional
sequential algorithm as a function of the characteristics of modern
and possible future processor hardware. Future work is then
discussed before conclusions are given.

2. Literature review

Grid-based motion planners have been successfully used in
academic and industrial robotics applications for a number of
decades [5–7]. In contrast to topological approaches, metric-based
approaches provide precise measurements of the spatial layout
of an environment to the resolution of the configuration space
representation and sensor measurements. This property, therefore
allows a more optimal solution to be calculated than approximated
graph-based approaches such as open space road mapping meth-
ods. The main practical limitation concerns the computational
complexity of calculating a solution [4]. Often a compromise such
as reduced coverage area or lower resolution is applied to counter
this, at the cost of accuracy [8,9]. The required update rate when
new sensor data is made available is also a significant factor [10].
A common technique is to use a hybrid metric and topological ap-
proach to represent an environment [11]. Here small areas store
a metric-based representation with each area arranged globally via a
graph-based representation. This is employed as less detail is often
required to plan on a global scale, while detail is paramount when
planning through dense areas within an environment. This tech-
nique is akin to modern approaches for managing map deformity
and assisting in loop closure [12]. Although divide and conquer mo-
tion planning approaches allow more efficient generation of paths
they are still limited by the computational power available to a sys-
tem.

Over the course of the last half century, one of the main methods
of counteracting problems that were too computationally expensive
at a point in time was to wait for the next generation of hardware to
be released by chip manufacturers [13]. In recent years, however,
central processing units (CPUs) have began to reach their physi-
cal limit in terms of processing power [14]. The industry has begun
moving towards a multi-core architecture that side steps the phys-
ical limitations of a single processor. However, software engineers
must face increasingly difficult challenges in developing applica-
tions for the concurrent paradigm [14,15].

In addition to multi-core CPUs, Graphics Processing Units
(GPUs) currently have hundreds or thousands of processors de-
signed specifically for Single Instruction, Multiple Data (SIMD)
type calculations [16,17]. The continued increase in GPU perfomi-
ance is mainly driven by the computer game and interactive
entertainment industries, but an increasing number of academic
and industrial applications have seen GPUs used for non-graphical
applications [18,19]. This technique is known as general purpose
computation on graphical processing units (GPGPU) and has seen
applications and advancements in fields such as database query ex-
ecution [20] to DNA sequencing [21].

A number of GPU specific algorithmic techniques have arisen,
particularly from [18]. An important technique that the proposed
method takes advantage of is the Ping-Ponging Method, which
involves storing the gradual evaluated values of an occupancy grid
in two equally sized buffers of memory. Each iteration one buffer
is set as read-only, with the other buffer set as a write buffer.
Numerous kernels are then executed in parallel, with each re-
ferring to the read-only buffer for preexisting cell values and out-
putting the calculated result for a cell at that iteration to the write
buffer. Between each iteration the roles are reversed, and hence the
data bounces back and forth between buffers. This double buffering
method prevents race conditions occurring and the GPU automatic-
ically synchronizes each kernel between algorithm iterations.

Traditional motion planning algorithms based on Dijkstra's
algorithm are sequential in nature and they abide by the principle
of optimality [22,23]. Likewise, in a grid-based domain, each
individual cell is evaluated sequentially, as lower cost neighboring
cells are recursively calculated back to an initial zero-cost
destination cell. A technique previously presented in [24,25] shows
that cells can be evaluated concurrently in theory, producing a
quantitatively identical result to traditional sequential algorithms.

3. Background

The theoretical basis for the research presented in this paper
is summarized in this section and is based on the work presented
in [24]. At the core of each evolutionary step of the algorithm, a
kernel represented by Algorithm 1, is run on each cell in an
occupancy grid in the GPU. The kernel queries the global cost
values of the eight neighboring cells and then calculates a value
for the assigned cell based on Eq. (3.0.1). The kernel is run on
multiple cells in a given occupancy grid concurrently using the
aforementioned Ping-Ponging method.

**Algorithm 1** Kernel pseudocode run on each cell in an occupancy
grid.

```plaintext
best cost := undefined

N := set of 8-way neighbors of current cell

for n ∈ N do
    if ncost is defined then
        current cost := ncost + travelcost(n, current cell)
        if best cost is undefined or current cost < best cost then
            best cost := current cost
    end if
end for

current cellcost := best cost
```

\[
C^*(x; x_{goal}) = \min_{u \in U(x)} (C^*(x'; x_{goal}) + L(x, u))
\]

\[
x' = f(x, u)
\]

\[
x, u \in \mathbb{C}_{\text{free}}
\]

\[
u \in U(x)
\]

\[
L(x, u) = \begin{cases} 
\text{avg}(C^*(x), C^*(u)) \times \sqrt{2} & \text{if diagonal} \\
\text{avg}(C^*(x), C^*(u)) & \text{otherwise}
\end{cases}
\]

The initial *vanilla* implementation requested every cell in an
occupancy grid to be evaluated by the kernel at every iteration.
This approach involved a simple implementation, but lead to the
majority of cells being evaluated redundantly each iteration. For
example, cells that are a great distance from the initial zero cost
destination cell were continually evaluated as undefined for the
initial iterations of the algorithm, as the virtual wavefront of cells
being usefully evaluated had not reached the same area of the
occupancy grid yet. In addition, cells that are close to the initial
zero cost cell were redundantly reevaluated as the same value
repeatedly in the later stages of the algorithm's execution.

An initial counter measure to performing these redundant
calculations was also presented in [24] and is referred to as the
method of the Expanding Texture. The main aim of this method was
to reduce the number of redundant cell calculations for cells that

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1 A kernel is the name given to the small program that runs on many cores in the
GPU concurrently. It is identical code applied to a range of data. 
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